IMMORTALS OF SCIENCE

JAMES CLERK MAXWELL

and Electromagnetism

by CHARLES PAUL MAY

JAMES CLERK MAXWELL and Electromagnetism

THE GENIUS of the Scottish physicist, James Clerk Maxwell, lay in his unmatched ability to synthesize scientific facts. His mathematical brilliance caused him to become one of the giants in the history of theoretical physics.

Maxwell's chief contribution to the development of science was his monumental theoretical deduction predicting the existence of electromagnetic waves whose behavior was like that of light waves. Many 20th century discoveries in the electromagnetic field have evolved from his findings.

From theoretical reasoning alone, Maxwell proved that the rings of Saturn could not be solid and continuous. Heat, the kinetic theory of gases, color vision, and color blindness also were brilliantly investigated by him.

(see back flap)

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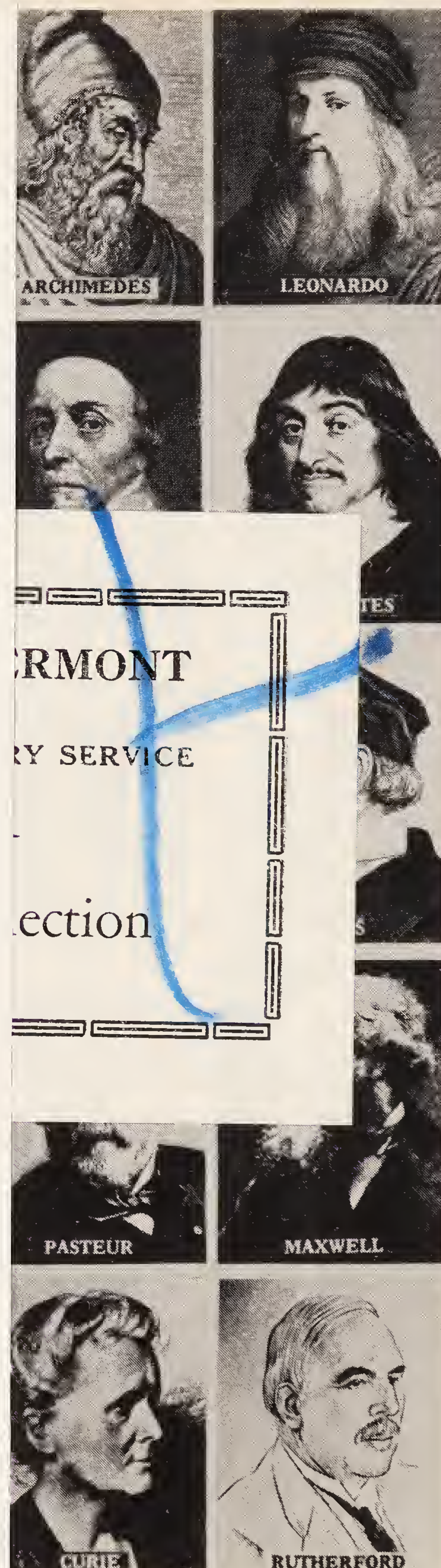

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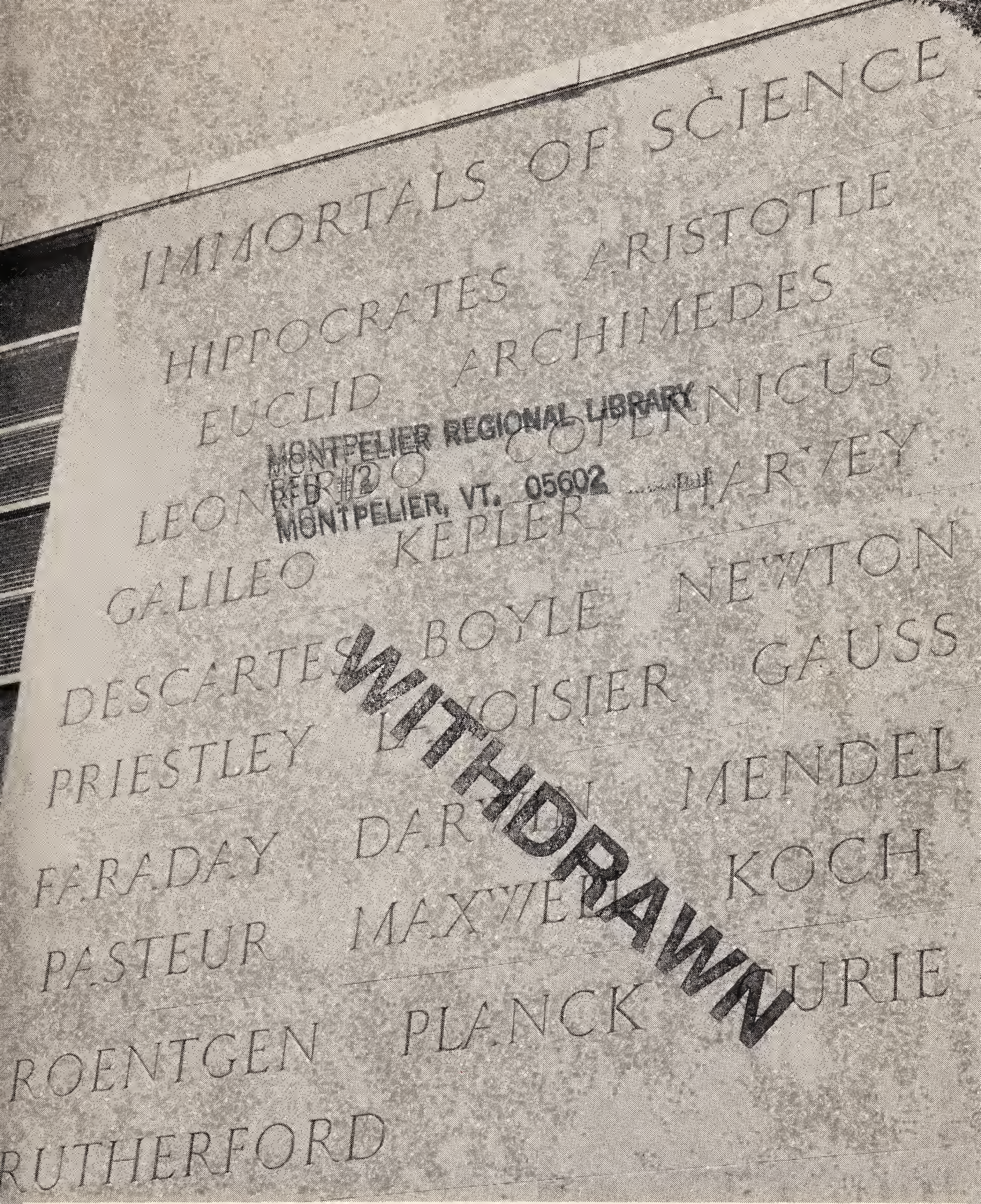

The Science Wall of Honor on the Charles A. Dana Hall of Science at the University of Bridgeport, Connecticut. This memorial was created to commemorate and perpetuate the names of the world's Immortals of Science whose fundamental discoveries in the field of natural science have yielded the greatest benefits to mankind's fund of knowledge and continue to improve its way of life. A world-wide poll was taken among leading scientists, educators and editors to select the names of the first twenty-five Immortals whose names are inscribed on this handsome wall.

JAMES
CLERK
MAXWELL

and

ELECTROMAGNETISM

James Clerk Maxwell

Immortals of Science

JAMES CLERK MAXWELL and *ELECTROMAGNETISM*

CHARLES PAUL MAY

Pictures by Robert Tidd

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Designed by Bernard Klein

To my mother and father

Contents

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James the Explorer

JAMES CLERK MAXWELL was born at 14 India Street, in Edinburgh, Scotland, on November 13, 1831. He was the only child in the family, for a girl, born before him, had died. In addition to the house on India Street, his father, John Clerk Maxwell, owned a country estate known as Glenlair.

Although this estate was not a great distance from Edinburgh, the roads leading to it were rough trails. Since it took two days to travel from the city to Glenlair by carriage, the family did not go back and forth frequently. When James was a few weeks old, he was

taken to the gray stone house on the country estate. There he spent his boyhood, and a happy one it was most of the time.

Like his father, James was sometimes called Clerk Maxwell. The name Clerk, which is pronounced as though it were spelled "Clark," was the name of his great-grandfather, Sir George Clerk. Sir George married his own cousin Dorothea Maxwell. This marriage brought quite a bit of property into the Clerk family. As is often done in Great Britain in such cases, Sir George added his wife's name to his own. Thereafter he was known as George Clerk Maxwell. And his sons, grandsons, and on down the line could also call themselves Clerk Maxwell if they wanted to.

Many people found it awkward to call James by both names, so those who did not call him James or "Jamesie" usually called him Maxwell. His father, however, was much more often called Clerk Maxwell.

At the surprisingly early age of three, James was already trying to find out what made things work.

"What's the go of that?" he would ask. Or, "What does it do?"

Locks and doors, for example, fascinated the boy. He wanted to know exactly how they worked. Fortunately, his father had plenty of time to spend with him, and would explain these things carefully if he could. However, being a lawyer rather than a mechanic, Mr. Clerk Maxwell found that there were many things he could not explain, and sometimes he would try to put the small boy's questions aside with vague answers.

This, he soon discovered, would not work. James insisted on an answer that would explain a mechanism simply and clearly. Then his father would have to admit that he did not know.

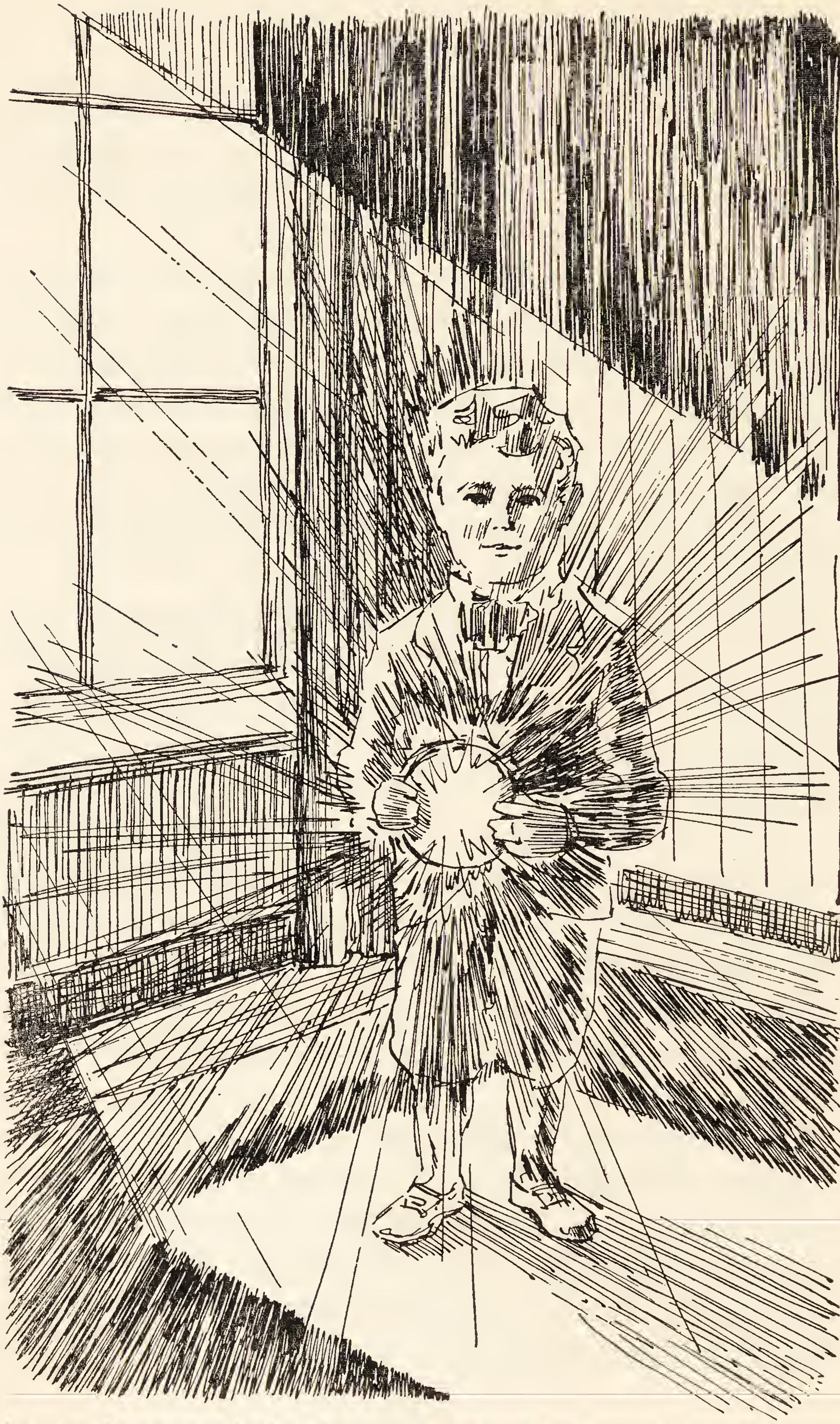
The Glenlair mansion had several servants, who were summoned by a system of bells. These were rung by wires that had to be pulled. "Jamesie," as he was called when he was small, could not leave the bells alone until he knew all about them. It was not just a game when he sent Maggy, his nurse, hurrying to see if a bell was ringing. Indeed, this was part of his very youthful discovery of science.

Soon young James knew which wire rang which bell. He could lead his father through the house and show him the wires going into their holes in the walls in one room and coming out of other holes in other rooms.

One day when James was about three, Maggy gave him something new to play with. It was a highly polished tin plate. In a matter of moments, James discovered that with the plate he could "catch the sun." He held the plate by the window, where sunlight was streaming in, and cast a bright reflection all about the room.

This discovery delighted him so much that he had Maggy run and find his father and mother. As they came into the room, he surprised them by throwing a beam of light from the plate into their faces.

"What is this you're about, my boy?" Mr. Clerk Maxwell asked, laughing.



James discovered that he could "catch the sun" with a tin plate.

"It's the sun, Papa," James explained. "I got it inside with the tin plate."

Mr. Clerk Maxwell was pleased, for it indicated that his son might become interested in scientific things. He had no way of knowing, of course, that James would one day start working very seriously with rays of sunlight—or that this work would yield important discoveries about colors, vision, and electromagnetism.

The elder Maxwell had told his son that someday he would explain about the moon and the stars. When the boy grew older, his father kept this promise. Mr. Clerk Maxwell would stand on the terrace outside the front door and hold his son with one arm while pointing out the different stars and the constellations with the other. Mrs. Clerk Maxwell would sit nearby and listen; it was a happy life for all of them.

The outdoor world was always exciting to the boy. A small river ran through the estate, and James followed it to the falls where it plunged into a larger river. There was also a dam on the small stream. Maggy, who kept a close watch on the boy when he explored the watercourse, had to explain how the dam worked.

Maggy knew it was a mistake to go exploring in her good clothes. She tied an old apron over her clean dress, and into it James would put rocks, feathers, and plants. These they took back to the house. If Mr. Clerk Maxwell was not to be found at once, James and Maggy stored the treasures in the kitchen until they could be fully explained to the boy by his father.

There was a crude cart, known as a "hurly," on the

estate. It was used to travel around the fields or about the neighborhood. Here was one more thing that James had to know all about. He learned to drive it when he was still small, and the neighbors often saw father and son going along the country trails in the hurly.

Mr. Clerk Maxwell was very serious about teaching James. On one occasion he obtained a chart of the stars, which was made of heavy paper and was cut up into pieces like a jigsaw puzzle. Each star was represented by a hole in the paper, the size of each hole indicating the brightness of the particular star. Big holes meant very bright stars, while small holes stood for dim ones. James learned to put this puzzle together quickly, after which he could go outdoors and locate in the sky the stars that were shown on his puzzle.

Dancing has long been a form of entertainment for people in Scotland. At the age of six, James was taken to a "barn ball." Some of the dancers gave exhibitions of special Scottish dances, but James did not pay attention. While other people were watching the dancers, the boy stood as close as he could get to the violinist in order to watch the bow go back and forth across the strings. He wanted to learn exactly how the sound of the musical instrument was produced.

Colors also fascinated James. He could tell one color from another at an early age, but as he grew older he was not content simply to know that an apple was red. He wanted to know *why* it was red. Moreover, he wanted to know *how* people knew that it was red.

One of his aunts admitted that it was most embarrass-

James and his father look for the stars that are shown on James's puzzle.

ing to be asked such grown-up questions by a boy. Not having a scientific mind, she was usually unable to answer him. To get his thoughts on more childish things, she hit on the idea of having him blow soap bubbles. What a mistake she made! As the bubbles caught the sun and glistened with all the hues of the rainbow, the excited boy began to ask even more questions about color.

One day James rode over the estate with his father to watch the hired men getting the hay in from the fields. For a while the boy simply watched the men pitchfork the bundles into a cart. Watching was not good enough, however, so James took one of the hayforks and helped load the cart himself. On the third swing he almost jabbed one of the men.

Everyone laughed, but the boy thought about this near accident seriously. Then he had an idea. If the cart went between two rows of sheaves, one man could load from one side and one could load from the other. They would not get in each other's way, as had sometimes happened before, and no one would be in danger of getting stabbed.

The field hands felt embarrassed for not having thought of this themselves. James's father, however, was not surprised. He was getting used to the remarkable ways in which his son improved on methods of doing things.

Not long after this, James was taught how to fish in the stream running through the estate. But the boy never grew fond of the sport. His first catch showed

him that the hook hurt the fish. As much as he wanted to study fish, he did not want to injure them. In fact, James felt the same way about all animal life. Even though he would catch insects and watch them closely, he quickly let them go if they showed signs of growing weak.

While his father served as James's first science teacher, his mother was his first instructor in reading, writing, arithmetic, and religion. She was an intelligent and capable woman, and James learned his lessons well. Soon the boy came to understand many things that usually had no meaning for other boys his age.

A seriously religious child, James could repeat many of the Psalms. He could also explain what Bible verses meant, showing that he thought about the Scripture as he was memorizing it. Just as his father taught him about nature, so his mother taught him to "look up through Nature to Nature's God."

In learning his lessons, James soon showed that he had an unusually remarkable memory. Throughout his life he could remember the discoveries of other men—when they had been made, and the circumstances leading up to them. Thus he seldom needed to read more than once the works of other men; after one reading they were fixed in his memory.

The happiness of James's childhood was shattered when he was eight years old. His mother fell ill, and for a short time she was in terrible pain. Nevertheless, whenever James came into her room, she would smile and sit up as though nothing were the matter. But in

time she grew so sick that she could no longer hide her agony.

At last James's mother became so ill that the family doctor felt an operation was necessary. Even though there were no *anesthetics* or pain relievers in that day, Mrs. Clerk Maxwell agreed to let him operate. The pain of the operation was terrible, but worst of all was the fact that it could not save her life. She died on December 6, 1839.

For days James was sad and quiet. He missed his mother very much. Then some one said to him that his mother had gone to heaven, and this cheered him a little.

"Oh, I'm so glad!" he said. "Now she'll have no more pain."

Sad as he was without her, young Maxwell felt better just knowing that her dreadful suffering was over. Indeed, throughout his life he would show this same unselfish concern for other people.

2

"Magic Disks" and "Remarkable Boxes"

SINCE Mr. Clerk Maxwell did not marry again, Miss Jane Cay, a sister of James's mother, came to Glenlair to look after James. She found that it was a bigger job than one person could handle.

James was constantly on the go. His main playmate was his cousin, Jemima Wedderburn—although she was eight years older than he was. Jemima did not have James's ability to invent things, but she was very good at encouraging James to do so.

One of their playthings was a "magic disk." This was a wheel on which figures of a person or an animal were drawn. Each figure was slightly different from the one next to it. When the wheel was turned, the figures blended together and gave the impression of being one figure in motion. Modern animated cartoons shown in motion-picture theaters and on television make use of this same phenomenon.

James wanted more "magic disks," so he made his own. Jemima was a capable artist, and together they could build and draw as many disks as they wished.

One of these disks had a cow jumping over the moon. Not only did the cow make the leap successfully, but the moon changed from new, to full, to old in the course of her trip. This was another expression of James's scientific interest in the night sky and its many changes. The moon also changed color slightly, for James was discovering that he could do wonderful things with colors when he made them flash rapidly in front of his eyes. This childish discovery led eventually to some of his most important experiments.

Another disk was even more ambitious, and showed James's interest in scientific accuracy. On this disk, a tadpole squirmed out of an egg, changed into a frog, and swam away. James knew exactly how this should be drawn, for he counted among his friends "the child of the mossy pool."

This "friend" was a frog in a backwater of the stream at Glenlair. James had discoverd tiny eggs in the stream,

and had watched them day after day. He saw them hatch into tadpoles and then gradually develop into frogs, one of which had markings so different from the others that James could always recognize it. It was the "life history" of this frog that James wanted on one of the magic disks, and he made Jemima draw it over and over until it seemed very real.

Aunt Jane Cay soon realized that she could not replace Mrs. Clerk Maxwell as James's teacher, so a tutor was hired. Since tutors were hard to find around Glenlair, Mr. Clerk Maxwell settled for a country lad who had a bit more schooling than usual, and he came to the Maxwell home to live.

When Aunt Jane or Mr. Clerk Maxwell asked James how he was getting on with the tutor, the boy gave no indication that anything was wrong. When the tutor was asked how James was making out, however, the young man replied that the boy was slow to learn.

This came as a surprise to everyone. James had always kept everybody alert because he was so quick to understand things. How could he suddenly have become as stupid as the tutor implied he was?

Then one day something happened that helped Aunt Jane to realize what the trouble was. On that day James decided to go boating on the duck pond in a wooden tub from the laundry house, using the big paddle from a churn as his oar. When the tutor discovered what James was doing, he ordered the boy to come ashore at once. James did not obey, and the tutor, bellowing

threats, tried to hook a rake over the edge of the tub in order to draw the boat to the bank.

At that point, however, Mr. Clerk Maxwell and Aunt Jane arrived, and said it was all right for James to go boating. Aunt Jane took particular notice of this incident. Now she began to understand why James could not learn from this young man. James needed to be led—and with kindness. He could not be forced into learning a lesson, but if someone showed him how interesting a subject could be he would study it willingly.

A few weeks after the duck pond incident, the tutor tried to "educate" the boy by yanking him about by the ear. The ear began to bleed, and the tutor's job came to an end. He left in November of 1841.

Since Aunt Jane had already announced that the boy was too far advanced for her to teach him, it was decided that he should go to school in Edinburgh. The school chosen was Edinburgh Academy, which was a day school. This meant that James would be at the school during the day but would leave after classes were over. He would not have to live at the school.

Because the country estate was more than a day's journey from Edinburgh, it was further decided that James should live with his cousin Jemima and her mother in the city. Jemima's mother, Isabella Wedderburn, was Mr. Clerk Maxwell's sister. Since Mr. Wedderburn was dead, Aunt Isabella and Jemima were both

glad to have the cheerful companionship of James around the house.

Snow lay on the ground when Mr. Clerk Maxwell and Aunt Jane brought James to the Wedderburn home at 31 Heriot Row in Edinburgh. The boy was carefully bundled up in a rough wool scarf that one of the servants had knitted for him, and he also wore a long cape-like overcoat that came down below his knees. Although he was sad at leaving Glenlair, the new adventure excited him.

On his first day at the academy, there was much for James to observe, but he got little chance to do so. Since he was a new pupil, he was naturally the center of much attention. However, his queer country-style clothes caused him to get off to a poor start.

The other boys were wearing jackets, but James arrived at school in a tunic—a belted, loose coat that came down below his hips. His shoes had square toes and were fastened with big brass clasps. The other boys wore shoes with rounded toes that were tied with black laces. James also had a frill collar instead of the plain round one worn by the other boys.

During the first lesson, James was aware of the snickers and stares from all sides. He could not help but realize how differently he was dressed from the others; nevertheless, he was warm and comfortable in his homespun suit, while the other boys were shivering from the cold.

Like most Scottish day schools of the time, this acad-

emy was run in the cheapest way possible. A fire was built only on the coldest days; even then, it kept only the teacher warm and the few pupils nearest it. However, the boys at the school were from the fashionable homes of Edinburgh, so they preferred to shiver and sniffle rather than dress in any garment that was not then in style.

After the first class there was a break of several minutes. The teacher, Mr. Carmichael, must have been aware of what would happen. Even so, he did not remain to keep order. Perhaps he thought the new boy needed a lesson from the others.

James was immediately surrounded by nearly all of the sixty-five boys in the group.

"Where did you find those shoes?" one boy promptly asked.

"Isn't that your sister's tunic?" asked another.

Suddenly someone caught hold of young Maxwell's collar. When James turned on him, other youths stamped hard on his square-toed shoes. This commotion was soon broken up by the return of Mr. Carmichael, but the teacher paid no attention to James's rumpled condition.

And so the day continued. When James returned to Heriot Row that evening, his collar was torn, his shoes were badly scuffed and dented, the lower part of his tunic was gone, and the rest of his clothes were torn and smudged.

James's good nature, however, showed no signs of

having been hurt. He was laughing, and gladly repeated the account of his first day at school as though it had been a wonderful adventure. He even admitted that he already had a new name—"Dafty"—and he seemed to be proud of it!

After that first day at Edinburgh Academy, Aunt Isabella suggested that another school might be found for James. The boy would not agree to this, however, and returned to Mr. Carmichael's classes. Gradually the other boys accepted him to a degree. Although he never really became one of them, some boys finally began to call him by his right name.

Most of Maxwell's classmates played school sports such as rugby and cricket, but James showed little interest in these. He joined the others now and again in marbles or in spinning tops, though later years showed that top spinning was more than a game with him. It became a part of his life's work in science.

Any bee or mouse that appeared on the grounds instantly caught Maxwell's eye, and off he would dash to investigate. At times he would amuse the other boys by demonstrating how a frog jumps, and he also liked to swing in the trees on the academy grounds.

The work James did in class, however, indicated that his mind wandered far from the academy. He did not make a good showing. Although Carmichael was considered a better than average instructor, he failed to inspire young Maxwell. Latin, especially, seemed dreary

to James. The country tutor at Glenlair had already made him dislike the subject, and Carmichael was not sufficiently talented to bring the language to life for James.

Besides, the boys around him gave him no peace when he was reciting. They made odd noises or funny faces to bother him, causing him to forget what he was going to say. Thus James began to hesitate in his speaking. In time, unfortunately, the faltering manner in which he recited carried over into the way he talked to people outside the classroom.

City life did not agree with James as well as country life had. He missed school frequently because of illness. Mr. Carmichael must have wondered if the lad would ever get an education.

Actually, James *was* getting educated—by himself. There was a large library at "Old 31," the name James gave to Aunt Isabella's house at 31 Heriot Row. The boy would have read all the books in the house if Aunt Isabella had let him. When she saw how eagerly he read everything, she hid away those novels that were about adults and that were not meant for younger readers.

The happiest times for young Maxwell were the weekends which his father spent at "Old 31." Then James and Mr. Clerk Maxwell would roam the streets looking for new sights. One day they went to nearby Salisbury Crags where they could see the different strata, or layers, of rocks up the sides of the bare cliffs.

Mr. Clerk Maxwell explained how the rocks had been built up layer upon layer through the ages.

And one February day in 1842, Mr. Clerk Maxwell took James to see devices called "electro-magnetic machines." Although no one realized it then, this was one of the most important days in young Maxwell's life.

"Electro-magnetic machines" were new at this time. In fact, it was only a few years earlier, in 1831, that Michael Faraday had discovered how to make a magnetic field produce an electric current. Although Faraday's first dynamo, or "electro-magnetic machine," was very crude, he and others had gone on to produce better ones in the years that followed. The one that James Clerk Maxwell saw in 1842 awakened in him an excitement that few things before had been able to do. He wanted to know all about the machine and about electricity as well. Soon, he would do this—and much more.

Meanwhile, as the boy grew more used to Edinburgh, to the academy, and to the other boys, he began to do better in school. Oddly enough, however, he did his poorest work in arithmetic. This is surprising in view of the marvelous uses to which he was able to put mathematics in later years. But, although James's schoolwork improved, his faltering manner of speaking did not leave him. It became a defect that he later had to force himself to overcome.

In addition, James was also finding out that he had to use strong methods to win the respect of the other boys. One day several of his classmates took to stepping on

his heels at every opportunity. Unlike some other tricks they had played on him, this one did not appeal to James's sense of humor. He lost his temper and turned on them. He knocked two of them down and sent the others scurrying out of reach. After that they did not tease the lad from Glenlair so much.

James's health also began to improve after a time. His outdoor life at the country estate had given him a muscular body, and the other boys began to admire his strength. They often urged him to become more active in sports, but the only one he particularly enjoyed was swimming. In this he would join them, although he sometimes startled or amused them by pretending to be a frog.

Dancing, too, was considered a proper, even an important activity for boys of good families. James proved to be especially good at dancing, and he delighted in the complicated patterns of the Scottish reels. Those that were unusually difficult, such as the lock-step, he loved to dance the most.

James regularly attended two different churches on Sunday. His father took him to St. Andrew's Presbyterian Church in the morning, while Aunt Jane Cay took him to St. John's Episcopal Chapel each Sunday afternoon. As a result, young Maxwell acquired a broad picture of religion.

There was a Royal Society (of art and science) in Edinburgh, and on December 18, 1843, Mr. Clerk Maxwell took his son to a meeting of this scientific and cul-

tural group. Recent scientific discoveries were discussed, and some members doubtless talked about new developments in mathematics. In any case, James began to show more interest in mathematics after that.

A few months later, in fact, James began to build geometrical shapes out of heavy, cardboard-like paper. Amazingly enough, he was not yet studying geometry in school, and it remains a mystery as to how he had the knowledge to do this work.

First, he built a cube. To do this required careful use of mathematics to make all of the sides and all of the angles exactly the right size. A cube, however, with its six sides all exactly alike, was only a start for James.

Next he constructed a tetrahedron, which is a type of pyramid. It has only four faces, but it is more difficult to build than a cube because it must be made of triangles rather than of squares. Three faces of a tetrahedron form the sides of the pyramid, while the fourth face forms the base.

Having constructed this shape successfully, young Maxwell tried still more difficult geometrical figures. A regular dodecahedron has twelve faces. They are all the same size and the same shape and each one of them has five equal-length sides, but to fit them together to form a solid "box" is not an easy matter, for the lengths of the edges of each face and the sizes of the angles must be exactly right. To build a dodecahedron would be a job to keep a student scientist busy, yet James was able to make one.

Young Maxwell, at the age of twelve, could build complicated geometrical shapes.

Still not satisfied, Maxwell, who was not yet thirteen, built even more complicated figures. In a letter to his father he admitted that he did not even know the names of these figures, but this did not keep him from making them.

These amazing "boxes" were the first clear sign that young Maxwell might some day do great things with mathematics.

3

A Discovery of Importance

IN THE FALL of 1844, James Clerk Maxwell and his academy classmates were ready for advanced work that took them out of Mr. Carmichael's hands. They now studied under the Rector of the school, John Williams. James found him to be a more likable instructor than Carmichael. As a result, his work showed further improvement.

The Rector took an interest in young Maxwell's manner of reciting. He pointed out that an educated man

did not "hum and haw" or make unnecessary pauses while speaking.

James was amused that the Rector should say this to him, for Mr. Williams himself had a trick that amounted to practically the same thing. Instead of pausing, he threw in unnecessary words while collecting his thoughts. He would say "yes, yes," or "that is to say," and other such space fillers when he needed a few seconds to plan the rest of a sentence.

Even so, the boy respected the Rector and realized the wisdom of the advice. Therefore, he devised a plan to help himself get over his hesitation in speaking.

When he stood to recite, Maxwell faced a window of the classroom. At home he drew a large picture of this window. Then he wrote his lessons in the spaces of the window frame as though he were writing them on the glass panes of the window. In that setting, he would memorize them.

In class the next day he would stare at the window frame, and in his mind he could see the words written on his picture at home. Without faltering, he would recite his lessons almost perfectly.

Gradually this trick improved his speaking ability and he found that he relied less and less on his artificial aid. Even so, some hesitation in speaking remained with him throughout his life.

The advanced work at the academy introduced James to formal geometry for the first time. For this subject the boys had a separate teacher, a Mr. Gloag.

Gloag was a humorous man and could give more life to his subject than Carmichael had been able to give to arithmetic. Stimulated by this teacher, young Maxwell at last took a real interest in mathematics at the academy.

Meanwhile, Maxwell was forming friendships with a few of his classmates, especially with a boy named Lewis Campbell. Campbell's family had moved to Heriot Row, which gave the boys a chance to walk home from school together. Campbell was an extremely intelligent young man and could understand much of what James talked about. Having someone to talk to on difficult matters gave Maxwell more courage to explore complicated subjects. As a result, his marks in school grew steadily better.

At this time in Scottish schools, there was much classroom competition. Moreover, it was encouraged by the instructors who thought that it produced better scholarship. In 1845, James won several honors. He won first prize for English, the medal in mathematics, and one of the prizes for scholarship.

His friend Campbell got six prizes! This caused some friction between them at the time. One of the instructors in later years hinted that their rivalry was not altogether friendly. Both young men denied this, but it is possible that the teacher was right. The friendship between Campbell and Maxwell long outlasted school competition, however, and after a while they forgot any anger that may have arisen between them.

Mr. Clerk Maxwell was well pleased with the awards that James received. To give his son encouragement, he started taking the boy regularly to meetings of the Royal Society of Edinburgh. The discussions that James had with his father after the meetings proved to Mr. Clerk Maxwell that the boy understood most of the lectures he heard.

The elder Maxwell also began taking James to the Edinburgh Society of the Arts. Aunt Isabella, Aunt Jane, and Cousin Jemima all had artistic talent, so that James was continually exposed to their efforts. Thus it is not surprising that he also became interested in art.

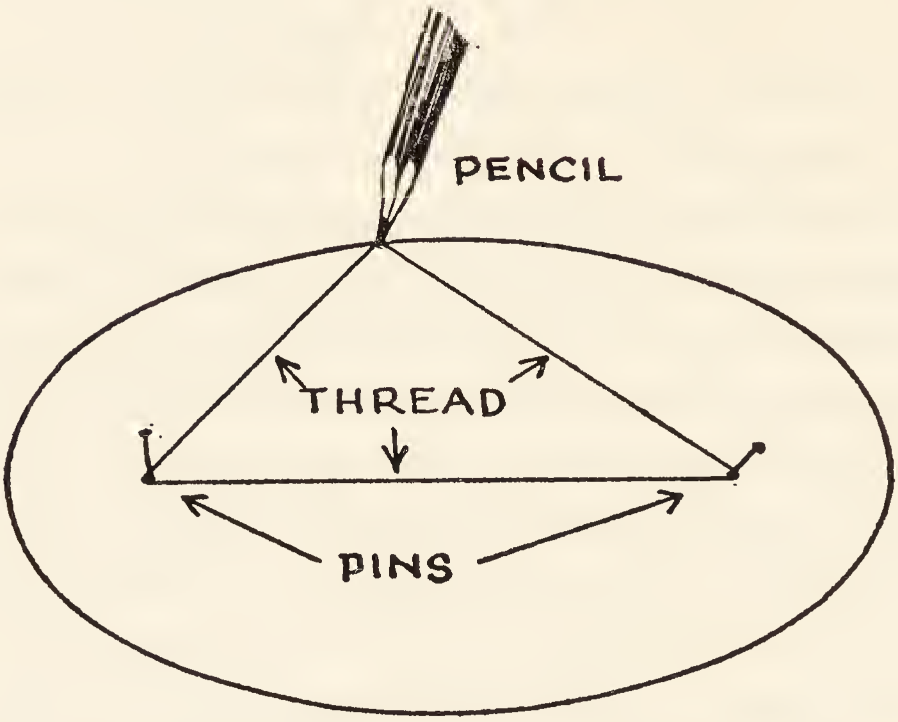
At some meetings of the Society of the Arts, James heard lectures by an artist named D. R. Hay. This man was trying to show that beautiful shapes and color combinations could be produced by using mathematics. This made a great impression on young Maxwell.

Actually, Hay interested mathematicians more than he did other artists. While he never became an outstanding figure in the art world—his works were too mechanical—he nevertheless was responsible for launching James Clerk Maxwell on his scientific career.

Mr. Hay drew curved figures in an artificial way. He put a loop of thread around pins and then ran his pencil around the inside of the loop. The pins would allow the thread a limited amount of freedom, and the pencil would be forced to follow a certain path.

For instance, a loop of thread around one pin made it possible to draw a circle. Again, a loop around two pins

placed a distance apart allowed the artist to draw an ellipse, which is a curved figure that is longer than it is wide—a kind of "squashed circle."

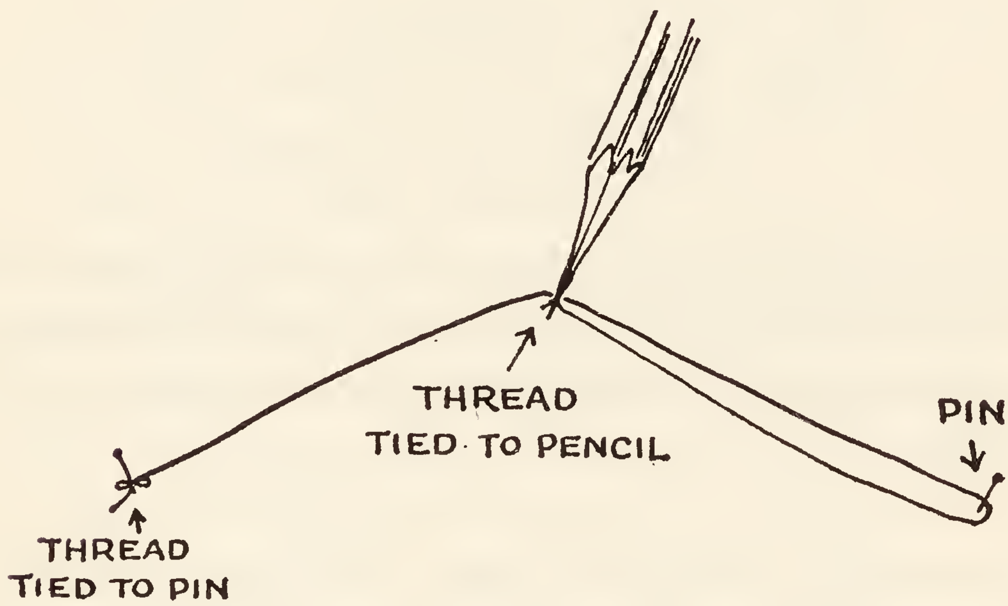


An ellipse drawn by using a thread looped around two pins.

Soon James himself began experimenting with thread and pins. He drew circles and ellipses, just as Hay did, and he discovered that the length of the thread determined the size of the curved figures he was able to draw. When he used two pins, he found that the distance between the pins determined the size and shape of the ellipse that he could draw. If the two pins were close together, the ellipse was really almost a circle. But if the pins were far apart, the ellipse would be shorter and more narrow even though the length of the thread did not change.

However, young Maxwell was not satisfied just to repeat the work of another man. He tried still different experiments to see if he could draw other figures than circles and ellipses. Before long he found that he *could* produce other figures.

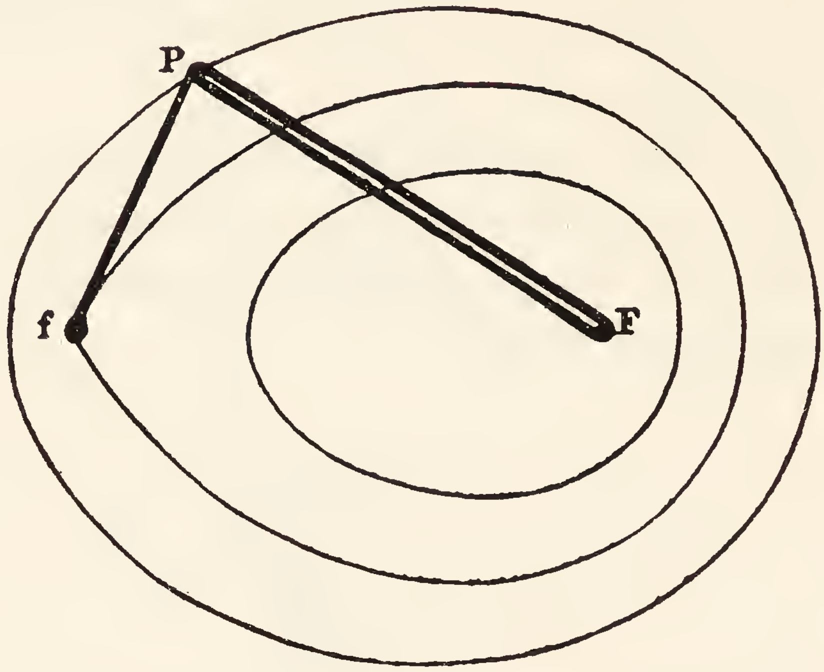
Instead of using a simple loop of thread over two pins, Maxwell tied one end of a piece of thread to one pin. Then he ran the thread around a second pin and tied the free end to his pencil.



Maxwell's arrangement of a thread tied to one pin, looped around a second pin, and then tied to a pencil.

With this arrangement Maxwell was able to draw an oval. An oval is similar to a simple ellipse, except that it is wider toward one end than toward the other. Eggs are usually wider at one end than at the other, so ovals are often said to be egg-shaped. As a result of his experi-

ments, Maxwell learned to draw figures with mathematical exactness.



A sketch from Maxwell's papers. Ovals of three sizes drawn by Maxwell's method. F *and* f *are pins, while* P *is the pencil.* F *is always inside the oval, while* f *can be inside it, on it, or outside it.*

By drawing dozens of ovals, Maxwell made further discoveries. One of these discoveries was that a clear relationship existed between the number of lengths of thread running to each pin and the distances the pins were from the pencil. Soon after he discovered this relationship, he was able to work out mathematical formulas that told him what sort of ovals he could draw.

In his imagination, however, the boy went far beyond pins and thread and pencils. He could imagine, for example, that the curves he drew were curved pieces of glass. He could also imagine that one of the pins was a

source of light and that the thread running from that pin to the curved piece of glass was a beam of light. The beam of light would be refracted, or bent, when it hit the glass. If the light came from outside the curve and hit the glass, Maxwell reasoned that with certain ovals it would be refracted just the right amount to shine through the spot where the second pin was.

Maxwell did not have equipment to prove that he was right about this, but he checked the formulas that he had worked out for drawing ovals against formulas other men had worked out for the refraction of light. He found that some of his formulas for ovals were the same as those for light refraction. Then he was sure that he was right about the refraction of light with an oval of glass of a particular amount of curve. The fact that he found the relationship between certain ovals and light refraction solely through the use of mathematical formulas makes his discovery all the more amazing.

James showed these experiments to his father. Mr. Clerk Maxwell was enough of a scientist to recognize that his son had probably performed experiments of importance. However, he wanted to be sure. He went first to Mr. Hay, in February of 1846, and showed the artist what James had done. The artist studied the drawings James had made and agreed that the boy had achieved something that he himself had failed to do, for he had never discovered how to make ovals with his pins and thread. Also, he had never recognized any con-

nections between the figures he drew and curved pieces of glass.

Thus encouraged, Mr. Clerk Maxwell went to a University of Edinburgh mathematician, Professor James Forbes. Professor Forbes and some of his associates were also impressed. When they learned that James was only fourteen, they were indeed amazed. They began to wonder if the boy had copied his figures and his formulas from the work of some other scientist.

The professors at the university looked through recent copies of mathematical books, journals, and papers to make sure. They could find nothing quite like the work Maxwell had done. Although the famous French mathematician René Descartes had done much work in drawing and classifying curves, Maxwell's experiments did not duplicate all of Descartes' work. Moreover, some of Maxwell's formulas were the same equations that Descartes had worked out by different methods from those that James had used. The fact that the formulas were the same helped show that Maxwell's work was accurate. Also, Maxwell's methods for drawing curves were simpler than the method Descartes had described.

The professors were even more astonished when they realized that Maxwell had gone beyond the great Isaac Newton and other scientists in relating refraction to the drawing of curves. They were at last convinced that the boy's formulas had all been worked out independently of other men and that his discoveries about ovals and refraction were original.

Professor Forbes made arrangements to read an account of producing ovals and of light refraction to the Royal Society. The paper was read on April 6, 1846.

James wrote this paper himself. It was titled *On the Description of Oval Curves and Those Having a Plurality of Foci.* By "plurality of foci" Maxwell meant that he used two or more pins, or points of focus, to draw his ovals. He was not allowed to read the paper to the Royal Society himself, however, because he was considered too young.

Before Professor Forbes read the paper, he edited it —that is, he changed it here and there to make it clearer. Even after it was thus simplified, it was such a complex report that some of the members present had trouble following it. In fact, throughout his life Maxwell had difficulty in making anything sound simple enough for other people to understand. Part of the trouble, of course, was that he seldom wrote about simple things. Yet even when he was just talking to friends he often had a hard time making them comprehend what he was trying to say.

Nevertheless, when this paper was read to the Royal Society of Edinburgh, Mr. Clerk Maxwell, Junior, as he was then called, had made his start as a highly original scientific contributor.

4

Maxwell Goes to Cambridge to Study

ALTHOUGH certain members of the Royal Society suggested that young Maxwell was ready to attend classes at the university, his father left him at the academy. The elder Maxwell felt that the boy was growing up too rapidly as it was, and that he should not enter the adult world at too early an age.

Oddly enough, when the mathematics medal was awarded at the end of the session, James did not win it

that year. Doubtless his outside experiments were taking up so much of his time that his schoolwork suffered.

During the next school year, however, James made a better showing, probably because he was not engaged in difficult work of his own. Then, too, he wanted to make a good record because it was his last year at the academy. This he succeeded in doing. When classes ended in the summer of 1847, he won the medal for mathematics as well as some other prizes.

In the fall of that year, young Maxwell entered the University of Edinburgh. In spite of his experience at the academy, he still did not try to dress like the other young men. Gloves, for example, were considered proper, but how could he feel the texture of a stone or a flower if he had on gloves? So he went without them.

Maxwell's odd behavior at the table could also be upsetting to his companions. While they were chatting politely about events of the day, they would suddenly become aware that Maxwell was not saying a word. Instead, he would be rising up, then slipping far down in his chair. Perhaps he would wag his head from side to side. But all the time he would be staring straight across the table at a water glass.

What Maxwell was doing was studying the way in which light passed through the glass. By changing his position now and then, he could see that other objects on the far side of the glass also seemed to change position and shape.

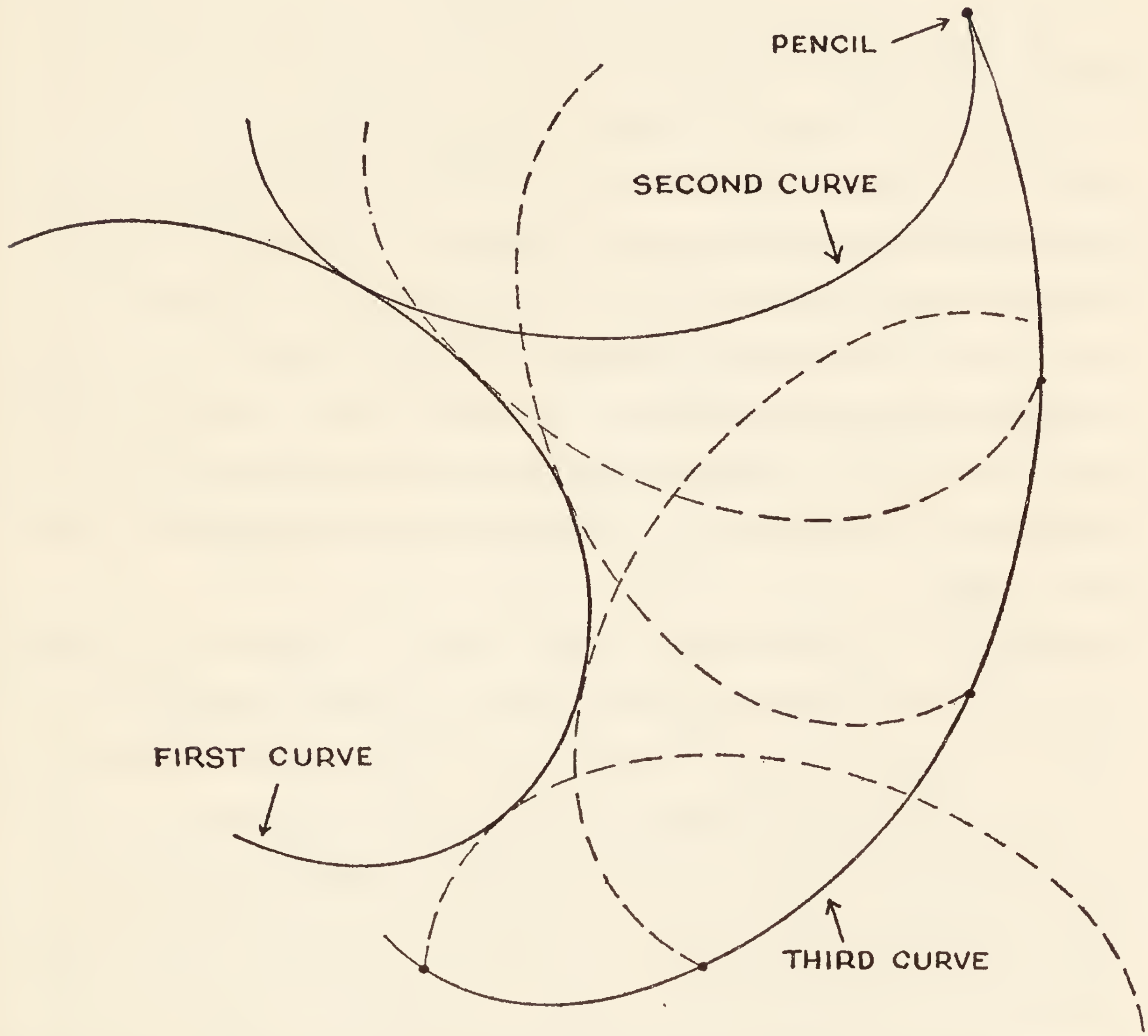
University work did not prove difficult for the young man. Consequently, he could continue to experiment in his room—whether he was living with Aunt Jane or Aunt Isabella in Edinburgh. And at Glenlair he set up his own laboratory in the attic over the laundry house. His workbench was an old door laid across two barrels; in all manner of jam jars and bowls he kept salt, blue vitriol, soda, sealing wax, charcoal, and other materials. Any discarded piece of glass or metal was something for him to add to his laboratory.

Young Maxwell continued to work with curved figures such as circles, ellipses, and ovals. The relationships between curves interested him greatly. In time, he was able to develop some formulas on this subject. This work proved to be so important that a paper on it, called *The Theory of Rolling Curves*, was accepted for reading before the Royal Society of Edinburgh. The young man was not permitted to read this paper, either, for he was considered to be still a child—even though he was seventeen when this reading took place on February 19, 1849.

A rolling curve is a curved line that moves along another line without slipping. The line that it moves along can be either curved or straight. Placing a pencil at some point on the curve that is moving, a third line will be drawn. This third line may be straight or curved, depending on the two lines that were used to start with. And, the relationship between the third line and the first two can be expressed in mathematical equations.

In one of the diagrams submitted with his paper on

rolling curves, Maxwell started with a simple curved line. Then, to move along this line, he drew a second curve. After this, he placed his pencil at the right end of the second curve. As the second curve rolled along the back of the first curve without slipping, it produced still a third curve.



Based on a sketch in Maxwell's papers, this drawing shows how one curve rolls along another curve and produces still a third curve.

It is as though he took one eggshell and rolled it around another eggshell. At no time would the one

shell be allowed to slide along on the other. It would always have to move by rolling. If the moving shell had a pencil stuck through one end of it, that pencil would draw a curve, which would be related to the curved surfaces of both of the eggshells.

Maxwell was not the first man to work with rolling curves by any means. It is thought by some scientists that Aristotle in ancient Greece may have started the work on a curve moving along another line. It was work that especially interested mathematicians, because one of the main reasons for doing it was to find the formulas to express the relationships between curves. However, many scientists before Maxwell had not given examples, so it was difficult to know how accurate their work was. Still others had given examples but had been unable to develop the equations that showed the relationships.

Maxwell pointed out that the few men who had worked out both examples and equations had dealt only with the most simple cases. Since Maxwell was not one to stop with simple cases, he could state that ". . . there are scarcely two curves, however dissimilar, between which we cannot form a chain of connected curves." As part of his proof, he continued developing the figure given above until he ended up with a complex diagram of about twenty lines. Then, in more than thirty equations, Maxwell expressed relationships between these lines.

This was only one of the examples given. He in-

cluded seven cases of curves rolling on straight lines, twenty-one examples of one curve rolling on another and giving a straight line, seven instances of curves rolling on themselves, and more than a dozen other examples of one line rolling on another. His purpose in going through so many cases was to give definite proof of the relationships that exist between lines.

At the same time that he was working with curves, Maxwell was also busy in three other fields. One of these was *galvanism.* This is an electrical term no longer in general use, but in the nineteenth century it meant the study of electric currents that were produced by chemical means. When two metals of different types were put in a bowl of acid and were connected by a conducting wire, a current was made to flow through the wire by chemical action in the solution in the bowl. It may well have been that, while experimenting with galvanism, Maxwell actually started work—in his mind—on his greatest achievement—a theory of electromagnetism.

Secondly, James was also interested in the *polarization* of light. Ordinary light vibrates in all directions at right angles to the direction in which it is traveling. Certain types of glass, however, can stop all the vibrations except those in one direction. Light vibrating in only one direction is said to be *polarized*, and Maxwell had a prism that would polarize light. Since his theory of electromagnetism later helped to explain how light travels through space, his experiments at this time with

polarized light may have started him toward this major work.

The third field in which Clerk Maxwell was working was the compressing of solids. By putting solids such as pieces of glass under pressure, he could learn how much they could be squeezed or twisted and still return to their original size or shape after the pressure was removed. Most of his experiments were performed with substances that would compress more easily than glass, however. He made up special jellies for this work, and he also obtained gutta-percha—a springy substance very similar to rubber. This led to his third paper—*On the Equilibrium of Elastic Solids*—that was read before the Royal Society, in the spring of 1850.

The paper opened with a statement that existing theories about the elasticity of solids did not agree with certain experiments that had been performed. For instance, the experiments of the Danish scientist Hans Christian Oersted showed that the theories of the French mathematician Siméon Denis Poisson were in error. Scientists before Maxwell had said that "Solid bodies are composed of distinct molecules, which are kept at a certain distance from each other by the opposing principles of attraction and heat." They went on to say that any change in the distance between the molecules caused them to exert a force on one another. They expressed this force in equations of elasticity, and these equations always contained what was called a *coefficient of elasticity*. A *coefficient* is a number that does not change,

but at the same time helps to express an *amount of change* in something else.

Maxwell, however, set out to prove that one coefficient of elasticity was not enough. He pointed out that in nature there are ". . . bodies which are in every intermediate state from perfect solidity to perfect liquidity . . ." He also said that even though both liquids and solids try to retain their *volume*, only solids try to keep their *shape*. And he called efforts to keep volume and shape *elastic powers*. Since there were two elastic powers, Maxwell said that the equations of elasticity must be worked out with two coefficients of elasticity.

In this paper, Maxwell freely admitted that two men before him had realized the necessity of having two coefficients. But one of them had not done enough experimenting to get exact figures for the coefficients of any substance; and the other had not worked out equations to prove the findings of his experiments. Thus, one of the most important features of Maxwell's paper was that he outlined enough experiments to show that his facts were right; likewise, he worked out the answers to his equations to show that they agreed with his experiments.

Maxwell gave fourteen cases to prove his point that two coefficients were necessary. Besides squeezing pressures, Maxwell used twisting pressures, the pressures of centrifugal force set up in spinning objects, pressures created by varying temperatures, and bending pressures.

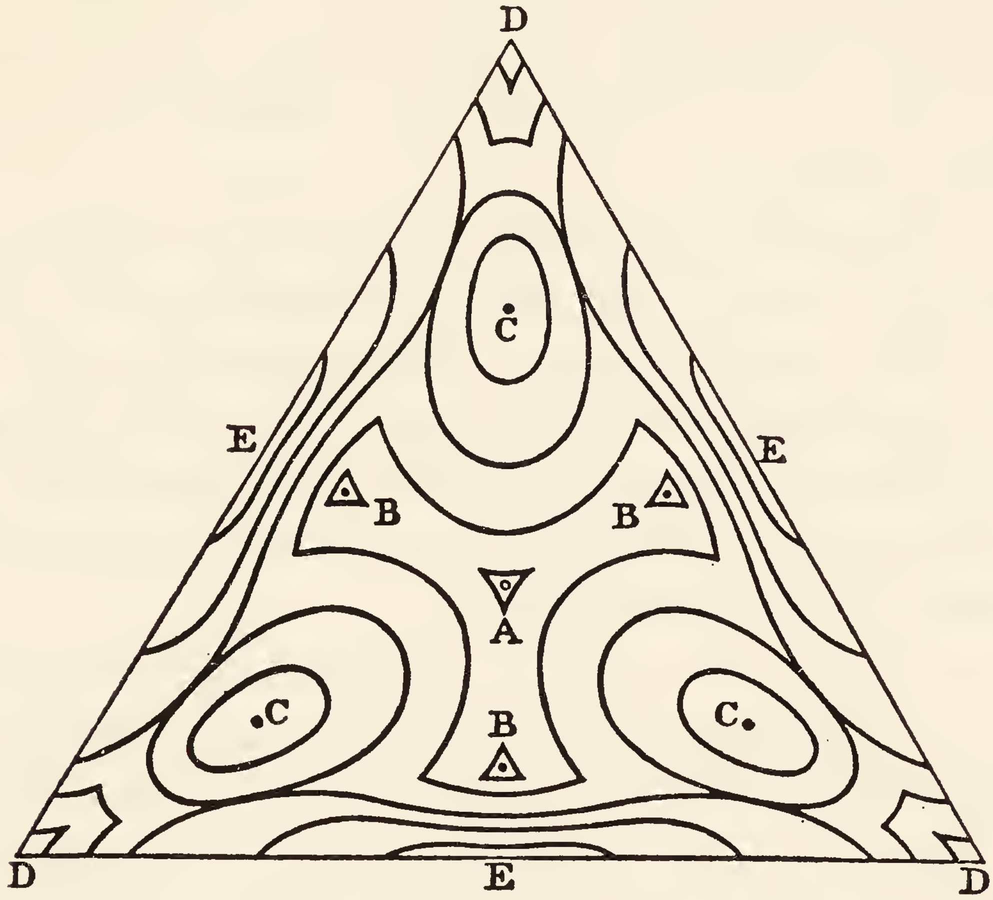
If he applied so much pressure that the substance would not return to its original size and shape, the experiment was a failure and he had to do it all over again. In later years, Maxwell was sometimes criticized for working out theories entirely from mathematical formulas instead of with experiments. But in his teens he was careful to back up theories with dozens of tests.

Because he was working with polarization of light at this same time, Maxwell combined his compression experiments with light experiments. He shone a beam of light through one of his transparent jellies before it was under pressure, and, as he expected, the light was bent. Then he put the jelly under pressure. He was surprised and delighted when an amazing thing happened. The beam of light bent, as he knew it would, but it came out the other side of the jelly as *two* beams instead of as one.

Breaking one beam of light into a double beam in this way is known as *double refraction*, and it can be done with certain prisms. Yet Maxwell had found a new way to bring about double refraction—by putting a substance under pressure. He found that with certain types of glass he could also get two refracted beams instead of one when he compressed them.

In still other experiments, Maxwell worked with a beam of polarized light. He found that circles or other patterns of light were set up in some substances when they were under pressure. One example that he included in his paper on elastic solids was a certain type

of triangularly shaped glass. Shining polarized light through it produced an interesting pattern:



Sketch from Maxwell's papers showing a pattern set up by shining polarized light through a piece of glass that is under pressure.

At A, BBB, and DDD the light was not affected. At CCC and EEE it showed the greatest amount of change. (Maxwell could have used this discovery of a pattern to look for flaws in other pieces of this type of glass. If there was a spot in the glass that was imperfect, it would disturb the pattern.) Once again Maxwell must have wondered how light traveled, since it could be changed by influences such as pressure.

It was impossible for Maxwell to build or buy all of the equipment he needed for his experiments. Much of his work, therefore, was done in the laboratories at the University of Edinburgh. His professors were so impressed with his talents that they allowed him free use of the laboratories.

At this period, however, Maxwell was often in too much of a hurry. He did not organize his material clearly and carefully, but in the excitement of a new discovery rushed to set forth his views and findings on paper. Often his papers were so complicated that, even after they were rewritten, it took a mathematician or a scientist to understand them.

Nevertheless, his papers and laboratory experiments convinced Professor Forbes that Maxwell should go on to Cambridge University in England. There the young man would be able to study under some of the finest professors in the world, and he would find more experimental apparatus to work with than at Edinburgh. The elder Maxwell, however, was reluctant to let James go. He had always hoped that his son would follow in his footsteps and become a lawyer. Also, being a Scottish Presbyterian, he was worried about letting James go to England, where that church was a minor one.

At last, however, Maxwell himself asked to go to Cambridge. After considering the matter thoroughly, his father agreed to his going, and so the young man went to Cambridge in the fall of 1850, after three years at the University of Edinburgh.

Since Cambridge University is made up of a number

of colleges, it was possible for Maxwell to choose among several of them. He spent the first few weeks at Peterhouse College, but then he transferred to Trinity. Trinity proved more to his liking; it was larger than Peterhouse, and students there were more independent. Immediately Maxwell amazed his professors and his fellow students with his wide range of knowledge.

Yet, at the same time, his associates were surprised at how badly organized his knowledge was. His letters during this period give many signs of this lack of organization in his thinking. When Maxwell wrote these, he would skip back and forth among numerous subjects; indeed, some of the longer letters were like puzzles to those who received them.

A private tutor was hired by Mr. Clerk Maxwell, and one of his first jobs was to help young Maxwell organize his thinking. The tutor also undertook to polish up some of the young man's country manners and to teach him to sit properly at table. In addition, an effort was made to keep the young Scotsman from cluttering up his room with all manner of gelatins, bits of glass, magnetized metals, and rocks.

The tutor had some success in getting his pupil to think a subject through from beginning to end. He even taught the young man to use the proper fork with the proper dish and to sit at the table without squirming. But try as he would, he could not eliminate the rocks and chips of glass and chunks of metal from Maxwell's room.

Being away from his home and family for the first

time, Maxwell tried out some strange schemes to determine what the best hours were for sleeping and exercising. For example, he tried exercising between two and two-thirty in the morning. He would run around his room, through the hall, up and down the stairs, and back to his room.

On the first night or two, the other occupants of the house were too surprised to know what was happening or what to do about it. Although his roommate complained, Maxwell continued this absurd routine for several nights. Soon, however, shoes, hairbrushes, and other objects came flying out through the doors along his route. Ropes were stretched across the halls which sent him crashing to the floor. Wisely, Maxwell went back to sleeping at the same hours that others slept.

Besides doing plenty of swimming and walking, Maxwell frequently went sculling, or rowing. He had a "funny," which was a one-man shell for sculling, and in it he often tried experiments. He would stand up to see how well balanced it was, and he did other stunts that sometimes caused the boat to capsize. He was in little danger, however, for he was an expert swimmer.

In the spring of 1851, Maxwell's work in mathematics at Trinity was good enough to earn him a scholarship. This honor gave him the right to skip over beginning courses. Now he could advance more rapidly, at his own pace. Young Maxwell enjoyed Cambridge much more after that. At this time, two Trinity professors, William Thomson and G. G. Stokes, both invited Maxwell to attend their small, carefully chosen classes. These

men recognized his ability and encouraged him to publish papers about his original experiments and discoveries. Soon these began to appear in the *Cambridge and Dublin Mathematical Journal.*

Even so, one of his friends wrote to another that Maxwell ". . . had great difficulty in imparting his ideas to others; consequently was not so clear a lecturer or writer as might have been expected." It was this difficulty that kept some of his papers from being published and that made it necessary for him to write others over again.

Yet this difficulty in writing clearly did not keep Maxwell from being accepted as a member of the Apostles, also known as the Select Essay Club. Only twelve students at Cambridge could belong to this group at one time, so membership in it was considered one of the highest honors that could be won. His papers written for this club were on a wide variety of subjects—from comments on Greek and Roman authors to what the planets are made of.

During the year 1853, the young man's curiosity led him into a rather strange path. He became acquainted with a group of students who were interested in the supernatural. He heard them talking about *seances,* or mystical meetings, at which spirits from another world made tables move, and at which other unlikely events supposedly took place. Although these things sounded improbable to Maxwell, he did not dismiss them without investigating.

At some of the seances people would sit around a table. Each person was told to hold his hands over the table with just the tips of his fingers touching the top. No one was to move his hands. If spirits from another world were present, they would make themselves known in some way, such as making the table tip or turn.

The candles were blown out so that the room was in darkness. Sometimes nothing happened, but once in a while the table would turn slightly or would tip. Many of the people present were certain that spirits were in the room and had made the table move. But Maxwell was quite sure that some person at the meeting had taken hold of the table in the darkness and moved it. When the candles were lit again, everyone but the person lighting them was sitting as he had before the lights were put out. Since Maxwell pointed out that this didn't prove a thing, he did not make himself popular with the other members present.

The same students were interested in what was then called "electro-biology." Electrobiology today is a science that uses electricity in the study of living animal tissues. But the electro-biology that Maxwell investigated was really hypnotism. One man was supposed to put another man to sleep by staring into his eyes and talking to him. He was then supposed to be able to tell the hypnotized person what to do or say.

When Maxwell went to a meeting, the man in charge, named Douglas, tried to hypnotize him. Douglas stared into his eyes and droned on and on that Maxwell was

going to sleep. Maxwell stared right back at him and remained wide-awake. Then Douglas tried to tell Maxwell that he had forgotten his name, but at all times the young man knew very well that his name was James Clerk Maxwell.

None of these activities kept Maxwell from going to chapel regularly or changed his deeply religious nature. By this time, he had read widely about different religions, and it was difficult to say whether he was a Presbyterian, like his father, or an Episcopalian, like Aunt Jane.

Even at holiday time, Maxwell kept himself busy. He visited steel mills or coal mines or other industries that he had not seen; even when he visited friends he was thinking or writing about polarization of light or other subjects. Due to the strain of all this activity, he became seriously ill in the summer of 1853. His ailment was described as a "brain fever," but it was more probably a nervous breakdown brought on by his trying to do half a dozen things at once.

Nevertheless, when he recovered, he returned to the lectures at Cambridge and threw himself into preparations for his final examinations. He took these after three and a half years at Cambridge, in January of 1854. The Senate Room at Cambridge, where the examinations were held, was so cold that he was advised to wear small muffs over his wrists and to carry a rug to wrap around his feet and legs.

Despite the cold, Maxwell did so well in the examinations that he achieved the position of Second Wrangler

in mathematics. "Wrangler" was a title given to a student who won honors in a subject at Cambridge.

In competition for the Smith's Prizes, which were the most important awards in mathematics, Maxwell tied with the Senior Wrangler. It is thought that he would have been Senior Wrangler himself if he had had the ability to express his answers more clearly to his examining professors. Even so, to complete his undergraduate work at Cambridge as Second Wrangler was an achievement for James Clerk Maxwell to be proud of.

5

Maxwell Studies Color Vision

SINCE MAXWELL had done so well in his undergraduate work at Cambridge, all of his professors felt that he should stay there and do graduate work. His father agreed to this, and so he remained at Cambridge. As a graduate student at Trinity, he was free to attend only lectures that interested him. He could also do more of his own research than before. For example, he had been interested in vision since his days of playing with "magic disks" as a boy at Glenlair. Now he started on a serious program of studying the human eye and the sense of sight.

His first step was to read what other men had written about this complicated subject. He also cornered all the color-blind persons he could find to ask questions about how objects looked to them. Soon he learned that red objects were somewhat hazy to these people. When possible, he would show them the spectrum—light broken down into its various colors—which he produced on white paper by means of a prism. The color-blind persons usually said that the red portion glowed faintly, but they did not say it was red. The orange to yellow part of the band of colors usually appeared bright yellow to them. From yellow-green to blue the spectrum often appeared bright but without any color; and in the blue and violet section they sometimes saw a strong blue color.

But reading and asking questions were not enough to satisfy Maxwell. He wanted to make a closer study of the eye in order to understand how it worked. What is more, he did not want to study eyes that could be obtained in a laboratory. He wanted to examine the eyes of living creatures—eyes that were still doing their job of seeing.

From what he had read, Maxwell knew that light passed into the eye through a small hole called the *pupil.* He reasoned that one man should be able to look *back through* the pupil of another man. Thus, the observer would then be looking inside the other man's eye. To be able to look through the pupil of a living person, however, Maxwell realized that some sort of instrument

would be needed. Such an instrument would need to magnify the inside of the eye in order to make it large enough for an observer to study. In addition, it would have to throw light into the eye; otherwise, the viewer would see nothing, for it would be like looking through a hole into a black box. Yet this light would have to be directed into the eye in such a way that it would not keep the observer from looking through the pupil at the same time. If any light were reflected off the thin membrane over the pupil, it could keep the observer from seeing into the eye.

Maxwell set to work to develop such an instrument. The first one threw too much light over the eye and cut off any chance of seeing through the pupil. But he kept on working, using a candle as his source of light. At last he was able to arrange the candle, a mirror, and a magnifying lens so that he could send a thin ray of light into the eye and see in at the same time.

What James Clerk Maxwell had produced was an *ophthalmoscope*—an instrument for seeing into the eye. Perhaps he had read about the ophthalmoscope that Hermann Helmholtz had invented in Germany in 1851 and used it as a pattern. Today this same basic instrument is a valuable aid to every eye doctor, although it has, of course, been greatly improved.

Some of Maxwell's friends were alarmed at the idea of having him shine the light into their eyes. They were afraid it would be painful or injurious. Maxwell, of course, could not really promise that it wouldn't hurt

the eye, for he had just developed it and didn't know exactly what it might do. Yet he himself was so confident that it would not injure the eye that he was willing to let someone else use it on him. His friends did not think this was a good idea either, and Maxwell began to wonder if he had gone to all the work of developing the instrument for nothing.

Then one of his friends brought Maxwell a pet dog and agreed to let him use the ophthalmoscope on the animal's eyes. If the dog felt any pain during the experiment, it would certainly bark or bite or in some other way let Maxwell know. When Maxwell looked into the creature's eye, the dog made no effort to pull away or to close its eyes. It stared back as though it were completely unaware that anything was happening.

The young experimenter was delighted with the results. For the first time he was able to look into an eye long enough to make a study of it. He could see the network of blood vessels at the back of the eye, which is the *retina.* The retina is the part of the eye that is sensitive to light. It is a thin membrane, and fine branches of the optic nerve connect it to the optic nerve and thence to the brain.

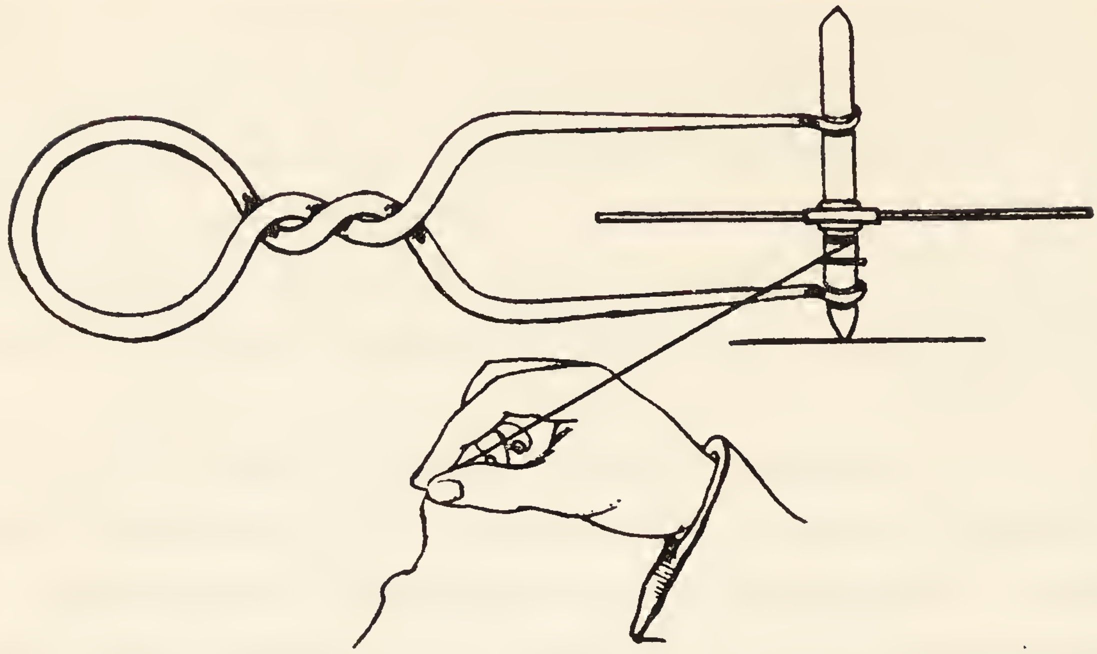
For some time after that, Maxwell worked primarily with dogs. He trained one so that it would look to the right, left, up, or down at his command. Thus he was able to study an eye while it was in motion.

As it became obvious that the ophthalmoscope was

not a dangerous device, Maxwell's friends were willing to let him experiment with them. He was then able to make sketches, some in color, of the insides of the eyes of humans. Soon, in fact, noted eye doctors were coming to Maxwell to see how the ophthalmoscope worked. His instrument was a great contribution to the scientific study of the eye and of vision.

At this same time, in the year 1854, Maxwell was also studying the formation of colors. By spinning different colored disks so that they seemed to blend together and become one color, he learned much about color formation. For example, he discovered that paint pigments are not the same as colors that make up light. Artists and scientists had long been saying that blue and yellow mixed together made green. When artists mixed their blue and yellow pigments together, this was true. But Maxwell was able to prove that when the blue and yellow that are in sunlight are blended, they result in a pinkish hue. Much of his work added proof to what Sir Isaac Newton had previously discovered.

The young scientist used a "teetotum"—a top—to make many of his experiments. This color top, as he called it, was a flat disk of tin; it was fastened to a vertical ivory axis, or center pole, around which it would spin. Around the rim of the disk were one hundred marks, all an equal distance apart. There was also a handle attached to the top, above and below the tin disk, so he could keep the device from wandering across the floor as tops usually do.



A sketch from Maxwell's papers. Maxwell's color top could be held by a handle (sticking out to the left) while it was spun by pulling a piece of string.

Maxwell went to D. R. Hay, the artist who had first interested him in drawing curved figures with pins and string, and asked him to paint a number of round disks of different colors. These paper disks were the same size as the tin disk on the top, and each one of them had a round hole in the center so that it could be slipped down over the axis of the top. There was also a slit from the outer edge of each disk to the hole at the center. This slit was cut in a straight line, and the slits in the different disks made it possible for Maxwell to slip part of a colored disk under part of another colored disk. By putting part of one color under another, he could have two, three, or more colors showing on the top at one time. The one hundred marks around the rim of the teetotum made it possible for him to know exactly

how much of each color he had showing. In this way, he could change the amount of color that showed by observing those marks on the disk of tin.

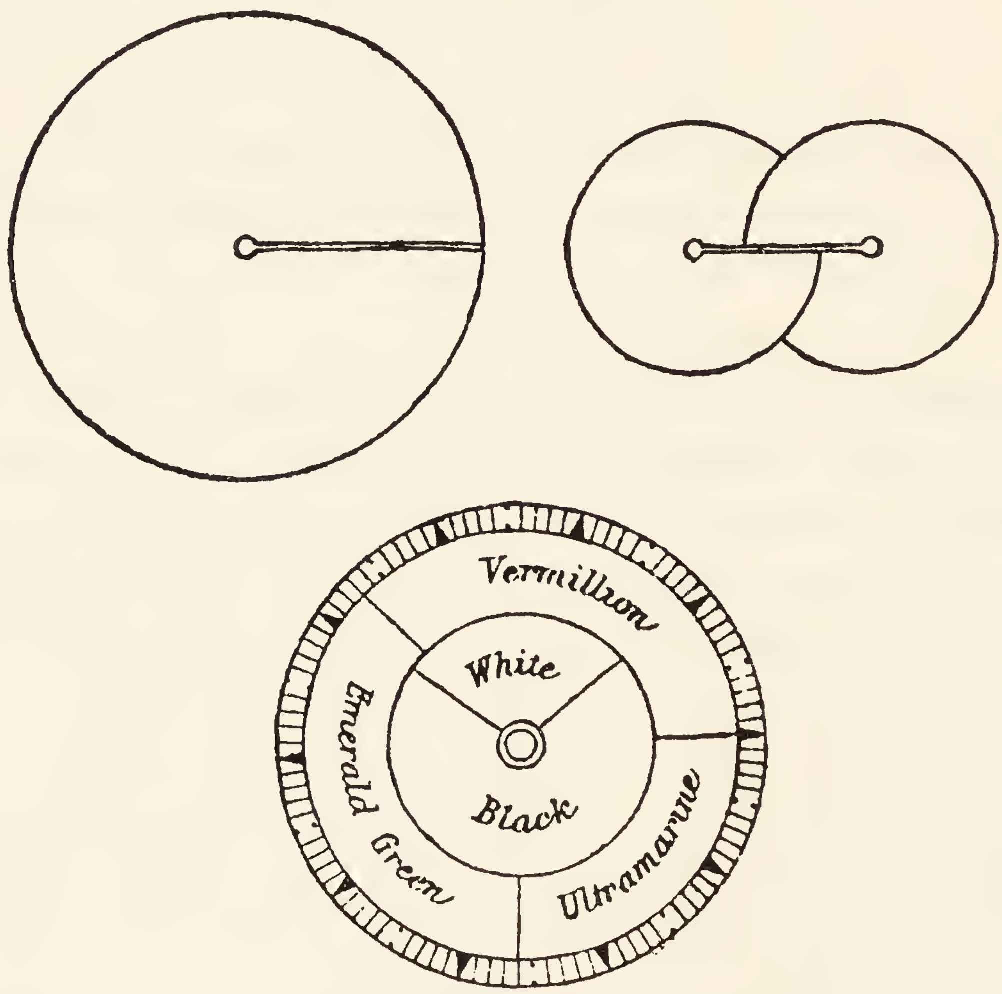
When Maxwell spun the top, the colors would blend and appear to be one color. Of course, there was no real physical change when the colors were made to blend by rapid spinning. Artists also produced one color by mixing other colors. When the mixing stopped, the new pigment remained; there was no separation back to the originals. Since the mixing of pigments in a bowl did not produce the same results as the blending of colors on his color top, Maxwell was able to prove to the world that the colors of objects and those of pigments may not appear exactly alike to the eye.

In other ways, too, the color top proved of major importance to Maxwell's investigations. With it he could match colors. If he knew that one color, say lavender, was formed of three other colors, he could find out those colors' exact proportions. He would put papers of the three colors on his top and spin it. Normally, he would start with equal amounts of each color showing; then he would turn the papers so that more of one would show, covering up part of another. By changing the amount of each paper permitted to show, he could finally match the lavender.

On the other hand, if he didn't know what colors the lavender contained, he could find a combination of colors that would match it. He would keep putting colors on his top and he would keep changing them until he exactly matched the lavender. Then he would

know what colors it took to make that color of lavender, and by counting off the number of marks on the rim for each color he used, he would know exactly how much of the other colors were needed. He could then express lavender as a mathematical formula—so much of one color plus so much of a second plus so much of a third *equaled* lavender.

Maxwell also had a set of color disks made that were



Sketches from Maxwell's papers. At top left is one color disk, while at top right are two of the color disks being put together by means of a slit in each one. Below is the color top with three full-sized color disks and half-sized black and white disks on it.

half the diameter of the tin disk of his teetotum. Thus he could put the full-sized paper disks on the top and some half-sized disks on it and work out color blends that involved more than three colors.

In addition, Maxwell used his color top in experiments with color-blind people to discover what color sensations their eyes did not react to. He would match one color by using three others, plus black and white, on his color top. Then he would have a color-blind person try to match the color. In each case, the color-blind person would finally cover one of the three colors almost completely. He would produce a match with two colors and white and black. Thus Maxwell would know that the other color was producing just a sensation of grayness, or lack of color, on the subject's retina.

Once he knew this, James reasoned that a pair of glasses could be made with colored lenses to help make up for the color that the afflicted person could not see. He made such a pair of glasses himself, using one red and one green lens. These glasses must have been quite startling to look at, yet they laid the groundwork for various types of tinted eyeglasses used today.

Maxwell found out other important facts from spinning his teetotum, too. He learned that if a person was allowed to watch the top for too long a time, he would start seeing colors that were not there. For example, the person would start seeing the *complementary color* of the one appearing on the disk. Two colors are said to be complementary when they mix together to form a neutral color, or gray. Maxwell also learned that it was best

not to let the person see the top when it was at rest. If he saw it at rest, he knew what colors were on it and he would try to go on seeing these colors even after the top was whirling rapidly. If, however, he turned his back until the top was spinning and if Maxwell had not told him what colors were on the top, the subject's observations of the blended color proved to be more accurate.

From all these experiments, Maxwell was finally able to say that there are three sensations in the eye concerning color—*shade*, *hue*, and *tint*. As an illustration of this, he took two colors that were both called lilac. He showed that one of them was darker than the other, so they differed in *shade*. One of them had a reddish appearance while the other one was closer to blue, which meant that they differed in *hue*. And one was more decided in its color—that is, "it may vary from purity on the one hand, to neutrality on the other." Or, it differed in *tint*. (The words "shade" and "tint" have different meanings to artists from those they had to Maxwell. So today artists speak of "intensity" instead of shade, and use "value" rather than tint.)

Maxwell was working on his color-top experiments when Christmas of 1854 approached. He might have stayed in Cambridge to go on with his work, but from Aunt Jane he learned that his father was not well. Consequently, Maxwell went home to Glenlair, where he found that his father was quite sick with a lung ailment. So serious was Mr. Clerk Maxwell's condition that the son decided not to return to Cambridge until after the

Easter holiday. This decision slowed down his research considerably, but so great was his concern for his father that he was willing to put his own progress aside to look after him.

In time, Mr. Clerk Maxwell was back on his feet again. Still, the young man did not want to return to Cambridge and leave his father alone. The elder Maxwell, however, insisted that his son should go. Yet the weeks away from the university had not been idle ones, for they had given Maxwell the opportunity to write about his color-vision work. The result was a valuable paper called *Experiments on Colour, as Perceived by the Eye,* which was sent to the Royal Society of Edinburgh in March, 1855.

The paper was read before the Society and it attracted considerable attention. The British Association for the Advancement of Science, a leading organization formed in 1831, became interested in James Clerk Maxwell. When it held a meeting in Glasgow in September of 1855, Maxwell was invited to demonstrate his color top to some of the members there.

Besides experimenting with the ophthalmoscope and improving it, "playing" with his color top, and working with friends who were color-blind, young Maxwell was also preparing himself for a fellowship examination. This was to be held in October of 1855.

Once before, Maxwell had tried for this honor and had failed to get it. The second time, however, he was better prepared and succeeded in getting the fellowship, which won him a teaching appointment at Cambridge.

Maxwell proved popular with the students who attended the lectures. Even after the scientist's hourly lecture was over, they would stay to ask questions and to get him to give further demonstrations on vision or the behavior of light. The interested attention these young people gave Maxwell was one more recognition of the original contributions he had made in this field of science.

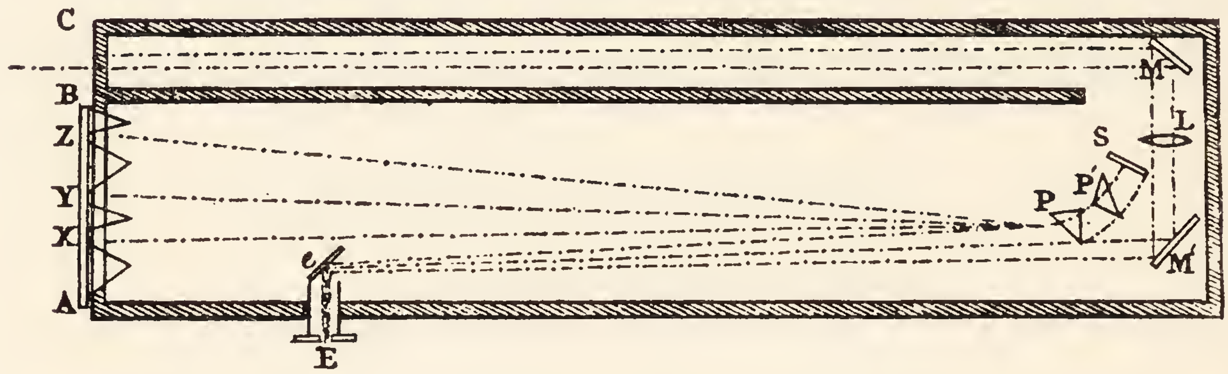
6

Maxwell's Work on Faraday's "Lines of Force"

JAMES CLERK MAXWELL was never really satisfied with the results obtained from his color top. The disks could never be colored so that he could be absolutely sure the colors were pure. When he had disks painted by different artists, those done by one were not exactly the same as those by another. And on a bright, sunny day the blends he produced would differ slightly from those obtained on a cloudy day.

To get still more accurate results, Maxwell invented

a "color box." His first one was big and clumsy, but he improved on it until he had one that was easier to handle. This final box was about three and a half feet long, eleven inches wide, and four inches high.



Sketch from Maxwell's papers showing the color box that he used in some of his most important color-vision experiments.

Light entered the box at E (see diagram) and was reflected by the mirror *e* to prisms P and P′. After passing through P′ the first time, it struck another mirror, S, and was reflected back through the same two prisms. A spectrum—the colors of the rainbow—was thus produced and was thrown on the far side of the box, AB. Where the spectrum fell, Maxwell had arranged a panel of slits, X, Y, and Z. They were movable, so that they could catch the light of different sections of the spectrum, and could be opened or narrowed to allow as much or as little light through as he wanted. By having them open just a fraction of an inch, Maxwell could let very pure colors pass through them.

Light also entered the box at an opening between B and C. This light came from the same source as the light entering at E, so that the experimenter was always working with the same light. This second beam of light was reflected by the mirrors M and M′ so that it fell on mirror *e* and arrived at the opening E, where it could fall on a white piece of paper. The person observing through E then had white light at E against which to compare the colors of the spectrum obtained at AB.

Maxwell had read Isaac Newton's works concerning color, and he set out to prove that Newton was either right or in error in thinking that red, green, and violet were the three *primary*, or major, colors of which the eye can be aware. After hundreds of tests, Maxwell found that he could reproduce almost all other known colors with different amounts of red, green, and violet. He could then say that Newton was correct in thinking that these three colors were very close to being the primary colors.

The writings of Michael Faraday also served to keep Maxwell busy. Faraday had discovered that iron filings sprinkled on a sheet of paper and held over a wire carrying an electric current arranged themselves in a pattern. This showed that the current set up a magnetic field around the wire through which it passed. Because the bits of iron arranged themselves in lines, Faraday said that the current set up "lines of force."

Faraday expanded Newton's theory that all bodies attract or repel one another, and the degree of attraction

depends on their mass—volume and weight—and their distance apart. The lines along which they are attracted or repelled are also lines of force.

Faraday was a self-educated man, and mathematics was not his strong point; consequently, he did not deal in complicated formulas when expressing his theories about lines of force. This left ample opportunity for James Clerk Maxwell, who was capable of turning almost any phenomenon into a mathematical equation.

When Maxwell started his own investigations of lines of force, he found that Faraday had already practically set up a formula. The more massive the bodies, the greater the force they exerted on each other, and the farther they were apart the less force they exerted. Therefore, it was a matter of working out how much of the force was caused by mass and how much was caused by distance. Newton had already done this for gravitation. Now Maxwell did it for electricity and magnetism.

Maxwell admitted that he did almost no experimenting himself. He relied on the work that Faraday had done. In doing so, he pictured in his mind a tiny particle charged with electricity and existing as a mere point in space. All other bodies and points in space around it would be pulling or pushing on it from a distance. If these surrounding bodies had an opposite charge from the original particle, they would be attracting it; if they had the same charge they would be pushing it away. All of these pushes and pulls combined would urge it to go in one certain direction. A line could be drawn through

that point representing the direction of the force acting on that electrified particle.

If that same particle were at another point in space a little distance from the first point, the direction of force would be changed somewhat because the particle would have changed position in relation to all other points and objects around it. A new line representing the new direction of force could then be drawn. Similarly, each time the particle's position was changed, another line could be made to show the change in direction of the force acting on it. Then, Maxwell said, one line could be drawn so that it became all the lines representing the direction of the force on the particle at each point in space. Since the direction of force would be a little different each time, the line would be a curve. And that curve would stand for the direction of the force on the particle at every point in space and would hence be a *line of force*. It would thus be possible, Maxwell said, to draw such lines of force until all space was filled with them.

A line, however, has no force in itself, so Maxwell imagined that the lines of force were tiny tubes with a liquid flowing through them. This liquid could not be compressed, so its volume was always the same. Then Maxwell proceeded to develop equations that would apply to such a liquid. But, since this liquid was just his imaginary way of dealing with Faraday's lines of force, the equations, when Maxwell had them finally developed, applied to the lines of force.

Maxwell read a paper, *On Faraday's Lines of Force*,

before the Cambridge Philosophical Society in December of 1855, and another one on the same subject two months later. The papers were well received, and Maxwell then sent them on to Faraday himself at the Royal Institution in London. The famous scientist sent Maxwell a sincere letter of congratulations. In this letter Faraday wrote, "I was at first almost frightened when I saw such mathematical force made to bear upon the subject, and then wondered to see that the subject stood it so well."

In this first trial at making use of Faraday's theories, Maxwell did not attempt to add new material to what Faraday had already accomplished. Instead, he put the older scientist's work into mathematical terms so that it could be used more easily by other scientists. Even so, his translation of Faraday's theories of lines of force into mathematical expressions is another of James Clerk Maxwell's outstanding achievements. He was only twenty-four at the time.

During this period, Maxwell also helped to spread adult education in England. A Mr. Maurice, one of the professors at Cambridge, was starting classes for workingmen. Maxwell offered his services to Maurice in setting up classes for laborers. He enjoyed helping other men in this way even when his own research suffered as a consequence.

Meanwhile, early in 1856, Mr. Clerk Maxwell had become so ill that he was no longer able to look after his law practice or run his estate. Moreover, Glenlair was far from medical help in case he needed attention

quickly. For these reasons, the elder Maxwell was advised to take up residence in the city.

Maxwell helped his father to move to Edinburgh. Although he wanted to take more time from his own studies to look after his father, Mr. Clerk Maxwell would not hear of this.

At about this same time, Professor Forbes, who had been Maxwell's closest adviser at the University of Edinburgh, learned that the professorship of natural philosophy was open at Marischal College, in Aberdeen, Scotland. He wrote to Maxwell in February of 1856, and suggested that the post might interest him.

Actually, Maxwell had not been looking about for teaching positions; he was content to be lecturing on a part-time basis and to have freedom for his own research at Cambridge. He knew, though, that his father had never fully approved of his going to England. If he could get the professorship at the Aberdeen school, Mr. Clerk Maxwell would be pleased that his son had returned to Scotland.

In addition, James would be closer to home and could spend even short holidays with his father. This was impossible while he was at Cambridge, for traveling to Edinburgh from Cambridge was difficult in the 1850's.

Therefore, Maxwell decided to apply to Marischal College for the professorship of natural philosophy. The idea of being a full-time teacher appealed to him now that he gave it serious thought. In many ways he looked forward to the chance to leave Cambridge, for he was seeing the same people and hearing the same views over

and over again. Going to another school would introduce him to new people and fresh views.

Since the British government held control of the colleges and universities, application had to be made to the Crown by writing either to the Lord Advocate or to the Home Secretary.

Since his father was a lawyer and since he was applying partly to please his father, Maxwell wrote to his father for any advice he could give about making application. The young man could not have done anything to please his father more. The thought that James would be returning to Scotland seemed to give him new energy. Immediately, he started looking into the matter and passed on to his son any information that he learned. The salary, it turned out, was about 350 pounds a year, or about $1,600—an ample sum to live on in those days.

Late in March, on a holiday from Trinity, Maxwell made the rough coach trip home to Edinburgh. He was delighted to see his father up and about. Mr. Clerk Maxwell was doing all he could on his son's behalf for the Aberdeen professorship, and the task seemed to agree with him.

Because Mr. Clerk Maxwell appeared to be in fair health, the doctor let him go out to Glenlair while his son was home. The trip was still not an easy one, but Mr. Clerk Maxwell was so happy to be at the estate again he did not seem to be any the worse for the journey. He showed the Glenlair account books to his son, and explained some of the things that would have to be done when he died.

The days passed quickly. Sometimes Mr. Clerk Maxwell could not sleep at night, yet at other times he rested well. Occasionally, he had trouble breathing, and he kept liquid ether handy to drink for it made breathing easier.

Since his father's health remained about the same, Maxwell made plans to return to Cambridge. He had lectures to give after the holiday, and he needed a few days to prepare them. He decided on April 4, a Friday, as the day to start the tiresome journey back.

On Wednesday night, Mr. Clerk Maxwell could not sleep. The younger Maxwell stayed up with his father all night and did his best to make him comfortable. Worse than the sleeplessness, however, was the state of Mr. Clerk Maxwell's mind. At moments he was badly confused. He could not remember where he was, or even recognize those who were trying to help him. Daylight was spreading across Glenlair on Thursday morning before he finally dozed off. When he awakened, he appeared to be rested. His mind was perfectly clear, and after breakfast he went out to the gardens to give instructions about getting them ready for spring.

Hearing his father come into the house just before noon, Maxwell went to the drawing room to see if he was all right. The older man sank into a chair.

"Lie down on the sofa for a bit," suggested Maxwell, but his father shook his head and simply sat looking out the window, across the fields of Glenlair.

Maxwell decided to go for the ether in case of a relapse. When he returned his father was still sitting by

the window. Then, suddenly, he gave a little cry and slid down a bit in the chair. His son held the ether to his lips, but he could not swallow. A few minutes later, Mr. Clerk Maxwell died.

In losing his father, Maxwell had also lost his closest friend. In deep sorrow, he remained at Glenlair to see to the funeral arrangements and give instructions for running the estate. For more than a week he was so occupied with Glenlair affairs that he had no time to think of anything else.

A letter from the officials at Trinity College reminded him that no matter what had happened, he must return to Cambridge to give his lectures. Maxwell returned about the middle of April. Once back at Trinity, he kept unusually busy, allowing himself little time to think of his loss.

Toward the end of April, Maxwell learned that he had been accepted for the natural philosophy post at Marischal College. This made it necessary for him to finish up his work at Cambridge, and he arranged to leave there in June. In the fall of 1856, he went to Aberdeen to begin his new work.

7

"Flying Brickbats"

When Maxwell lectured to the students at Marischal, he forgot that they were not as advanced as the young men at Cambridge. As a result, his teaching is never listed as one of his major achievements.

Maxwell was also nearsighted, which kept him from seeing the faces of his pupils clearly much of the time. Sometimes, however, he would pace among their chairs as he talked; then he would see their puzzled expressions. Immediately he would break off in the middle of a sentence or stammer around for a bit, trying to think of a simpler way to give his lecture. In the middle of this

confusion, of course, the young men in his classes would become more lost than ever.

Yet, despite his shortcomings as a teacher of undergraduates, he made a good impression on his pupils. His attractive face, half hidden by a black beard and sideburns, was certainly a friendly one. Moreover, he was so much more intelligent than most other teachers at Aberdeen that many young men managed to learn more from him than they did from the other professors.

Outside the college, Maxwell continued his program of holding classes for workingmen. Around Cambridge this had become an accepted practice, but it was strange to the townspeople of Aberdeen. They decided that Maxwell was a trifle odd to be doing something of this sort. Some of the other professors at Marischal, as well as those at the other college in the city, were also annoyed, for it made them appear lazy and unwilling to help the laboring class.

Thus, because of his "odd ways," Maxwell sometimes found himself in trouble. For example, students at Marischal were allowed to take only two books from the library at a time; on the other hand, teachers could take out any number they wished. Many of the teachers took out books for their friends among the people of Aberdeen and no one ever objected. When Maxwell took out an armload of volumes, however, someone became suspicious, for it was known that he had few friends among the townspeople. It was discovered that he was checking out the books to lend them to the students in his classes. Maxwell's explanation was that a college li-

brary should be for the students of that college; but after that he had trouble getting books whenever he went to the library.

When Maxwell wrote to friends at the end of the spring session of 1857, he indicated that his work had gone rather well. Quite possibly his teaching methods had improved in the course of the school year. He had always believed in self-improvement, as when he had made himself learn to recite his lessons without faltering and when he had tried to find the best hours for exercising.

Meanwhile, during his first year as professor, Maxwell had not set his own researches aside. He regularly found mathematical puzzles to perform, and continued to observe the stars and the planets, which he had been doing since boyhood. The phenomenon of the rings around the planet Saturn particularly interested him at this period.

In fact, the matter of Saturn's rings was then of interest to the whole world; moreover, a prize was to be given by St. John's College of Cambridge University for the best explanation of the motion of the planet's rings. Although the prize had been announced in 1855, it was not to be awarded until late in 1857.

Maxwell had already done a great deal of thinking about Saturn. In the spring of 1857, he decided to work seriously on a theory that would explain the motion of the rings.

Up to that time, there had been many guesses as to how the rings had been formed and how they moved.

Some men thought they were solid rings. Others believed that the rings were not solid, but that they were uniform—that is, whatever material they were made of was the same throughout.

The more Maxwell thought about Saturn's rings, the more he became convinced that the right explanation of their formation and movement had not yet been found. He was convinced that their motion was not just a simple whirling around the planet, as many people thought.

As always when he studied a subject seriously, Maxwell read what other men had written on it. He found that Christian Huygens, a Dutch mathematician and physicist, and Pierre Simon de Laplace, a famous French astronomer, had paid much attention to Saturn. Laplace had already pointed out why certain theories about the rings could not be true, and Maxwell used these same arguments, giving the Frenchman much of the credit for them.

It was generally agreed that the rings were spinning just fast enough so that centrifugal force—the outward pull caused by their flight around the planet—was balanced by the inward pull of the planet's gravity. If the rings were solid, Maxwell reasoned, the pull of gravity would be greater on the edge of a ring close to the planet than on that ring's outer rim. And at the same time, centrifugal force would exert more pull on the outer rim than on the inner one. This would naturally cause the ring to break apart in time. In other words, pieces near the planet would fall toward the planet, while pieces far from it would fly off into space.

There was only one kind of solid ring, Maxwell said, that could keep from being split apart by the double action of centrifugal force and gravity. This would be a ring that had a heavy weight at some spot on it. The attraction of this weight on the rest of the ring could prevent the ring from flying to pieces. Maxwell used mathematical formulas to discover that this weight would have to be four and a half times as heavy as the rest of the ring. Such a heavy spot on the ring would be observable as a sort of satellite, Maxwell said. Since no such phenomenon could be detected, he was positive that it did not exist and that the ring therefore could not be solid.

Even if the rings were entirely liquid in nature, as some men imagined, they would still be broken apart. The spinning would set up waves, and these would in time become great enough to cause the liquid to break up into drops.

On the other hand, if the rings were not solid, Maxwell decided, but were of the same uniform composition throughout, one ring would set up tides in another just as the moon sets up tides in the earth's oceans. And this, too, would cause them to break up, or at least to change shape sufficiently so that the change could be observed from the earth. He did point out that during the previous two hundred years, one of the outer rings had apparently grown broader. And also, the innermost ring, which had just been discovered in 1850, seemed to show signs of getting closer to the planet itself. However, none of the changes that had been noted were great

enough to indicate that the rings were in any way breaking completely apart.

The reason the rings did not break up, Maxwell concluded, was that they must be made up of *many tiny satellites*—"flying brickbats" he called them—which were in no uniform pattern and rotated at different speeds. In such a system, these tiny satellites would all be affecting one another and yet their influences would be continually changing because their different speeds would not leave any two satellites near each other for very long. Each satellite could change position in relation to other satellites in three different ways. First, it could rush ahead of others or fall behind them. Second, it could move closer to the planet or farther away. Third, it could move toward the top side or the bottom side of the ring. The changing relationships among all the satellites, according to Maxwell's calculations, would keep great waves from being created. Before any such wave could be started, the pull of one satellite would be gone and new gravitational pulls of others would intrude from different angles.

Maxwell also concluded that the rings closest to Saturn were made of the lightest material—something like "rain, hail, or cinders"—while the ones farther from the planet were heavier. This would explain why the inner ones did not fall into the planet and why the outer ones were not flung off into space. As Newton and Faraday had stated and as Maxwell had already shown in his work on Faraday's lines of force, mass and distance were both important in measuring the attraction between bodies.

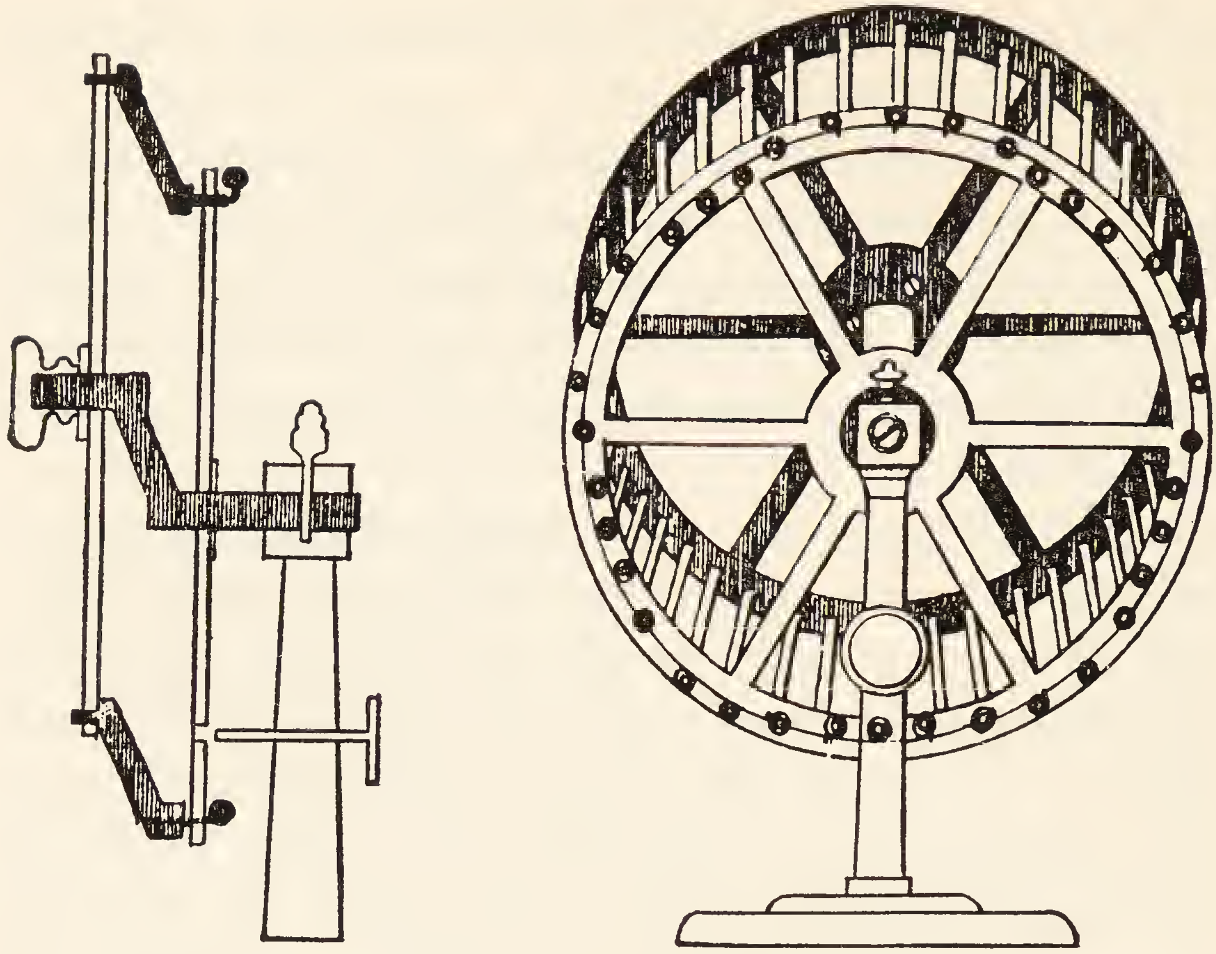
For this reason, the nearer bodies would have to be less massive than those more distant.

Moreover, this theory agreed with what astronomers had already observed. The outer rings were so dense that the planet could not be seen through them. But the innermost ring, at least where it was not hidden by the outer ones, was so thin that the planet could be seen through it.

Maxwell went so far as to invent a complicated device that had thirty-six ivory knobs, each representing a satellite, arranged at different distances from the edge of a large wheel. A bent axle ran from this wheel to a second wheel, and each satellite was also connected to the second wheel by a bent axle. When the second wheel was not allowed to turn and the first wheel was spun by means of a crank, each ivory knob rotated differently from most of the others. The scientist used this as a demonstration of how each satellite in Saturn's rings could have some degree of independent movement.

It is not surprising that Maxwell, now a very skilled mathematician, tied his theories together with precise mathematical calculations. Using the estimates that astronomers had made of the size and the density of Saturn, of the speeds of the different rings, and of the distances the rings were from Saturn, Maxwell could find the densities of the rings themselves. While making these mathematical calculations, he could also judge the estimates of the astronomers and narrow them down to more exact figures.

It took sixty-eight pages and more than two hundred



Sketches from Maxwell's papers. Side view (left) and front view of the satellite wheel that helped Maxwell explain Saturn's rings.

equations for Maxwell to compose his paper on the motion of Saturn's rings. This was a lengthy task, but he had it ready in time to enter it in the competition for the St. John's College prize.

While he awaited the results, Maxwell went on with other work. He was developing a new kind of top. Instead of blending colors, this one demonstrated the properties of rotating bodies. He called it his "dynamical top."

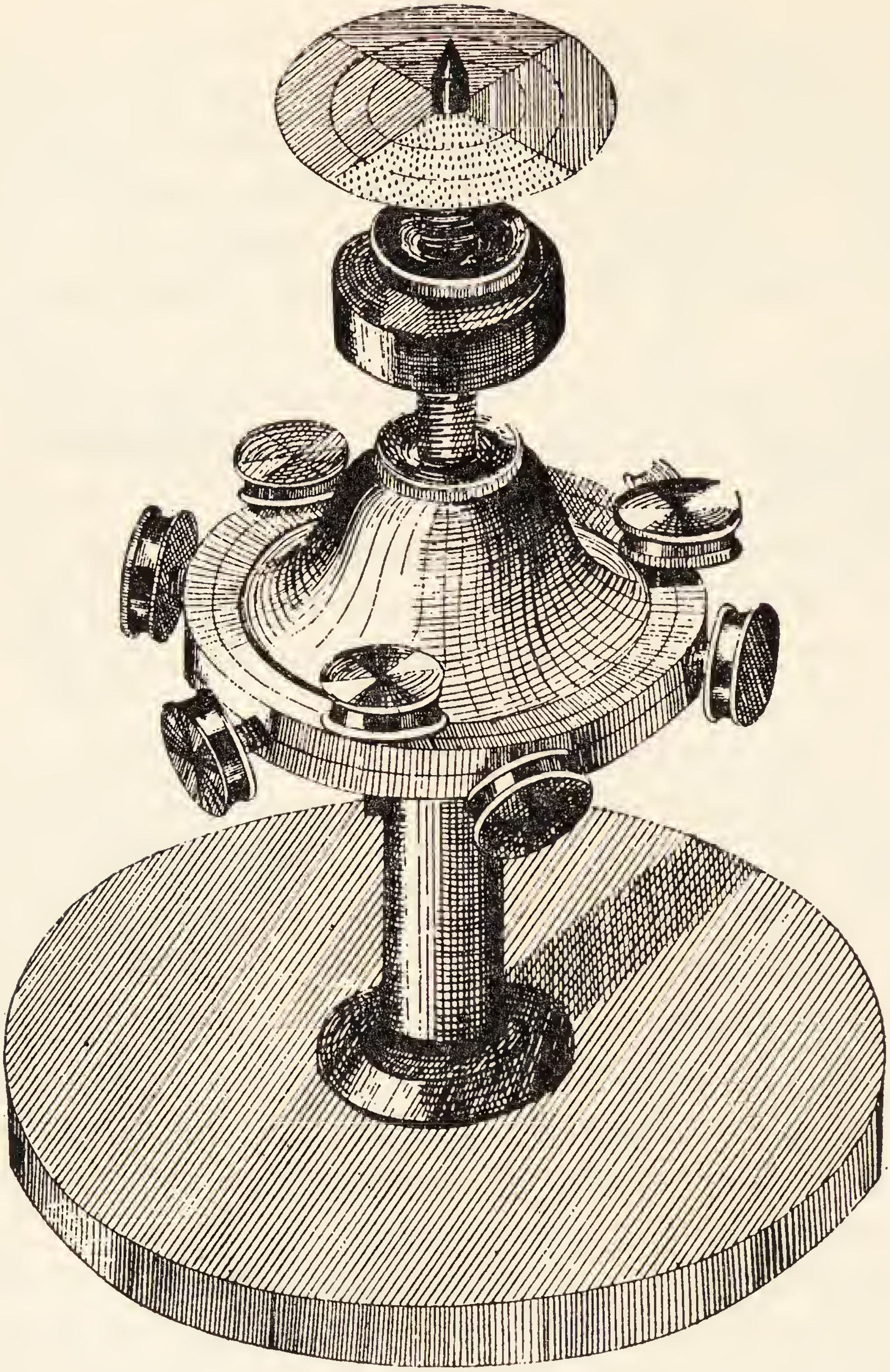
This top was made of brass in the shape of a bell. A long screw ran down through the center of the bell and

ended in a sharp point, for it was on this screw that the top spun around. There was a heavy nut on the screw, or axle, as Maxwell called it. This nut could be screwed up or down so that it could be put at the exact center of gravity of the top. The *center of gravity* of an object is the point around which all parts of the body are balanced.

On the rim of the bell were six holes spaced evenly apart. Heavy bolts could be screwed into these holes to change the weight, and, consequently, the center of gravity of the top. Maxwell could use two, three, four, or all six bolts at one time and have the top balanced by using the right holes. There were three more holes for bolts above the rim of the bell.

By using the bolts in a variety of combinations, Maxwell could see how different types of spinning bodies would act. Even an ordinary toy teetotum, he knew, does not stand in one place and spin, unless it is caught in a hole. Normally it moves along the floor. Maxwell was able to prove that whirling objects follow paths that are ellipses if they are free to do so. This was already known to be true of satellites, such as the planets, but the top made it easier for men to observe the phenomenon.

By changing the center of gravity of the top, Maxwell showed that the path of a whirling body was closely related to its center of gravity. He could make the top go in long ellipses, or in short ones that were almost circles. By comparing the orbits of heavenly bodies with the movements of the top, astronomers could predict



A sketch from Maxwell's papers. The dynamical top used by Maxwell in experiments that established his fame in mechanics.

more about satellites than they had been able to do before.

Maxwell also found colors helpful on his dynamical top. He used four—vermilion, chrome yellow, emerald green, and ultramarine—which all blended into gray when the top was turning perfectly. But if the top were wobbling even slightly, the colors would not blend. In this way, Maxwell could easily discover when he had the axle nut exactly at the center of gravity. In addition, he could study the paths followed by spinning bodies that were not perfectly balanced around their centers—that is, bodies whose geometrical centers and whose centers of gravity were not in the same spot.

All of this work with the dynamical top was not confined to one year. The first top had been developed by Maxwell a few years before, but it was the one that he had made in Aberdeen in 1857 which worked so well that it established his fame in mechanics. He continued to use it until the end of his life.

During the summer of 1857, Maxwell returned to Cambridge to work on his master's degree. Undoubtedly he was eager to hear how his paper on Saturn was making out in the competition, but he kept busy with his studies and with his dynamical top. In the fall he returned to his teaching post in Aberdeen. As the time for the prize to be awarded came closer, Maxwell grew anxious. He kept wondering if he had made any miscalculations in the paper.

Other scientists were doubtless feeling the same way.

To win the prize would be a great honor, and it would help establish a man's fame throughout the world.

The judges at this time were busy reading and evaluating the papers. If there were many as long and as complex as Maxwell's, it is no wonder that they did not rush through the task. Finally, however, they came to a decision—James Clerk Maxwell's paper was the winner. It is still regarded as one of Maxwell's most important scientific accomplishments.

8

Further Work

THE CITY of Aberdeen was in a turmoil when Maxwell returned in the fall of 1857. In addition to Marischal College, there was also a King's College in the city. Since these two institutions covered roughly the same subjects, it was rather pointless to have two separate schools. For this reason, there was a movement on foot to combine them into one university; however, the way in which this was to be carried out created a conflict.

Most of the good professors felt that the colleges should be fused—that is, classes of the same sort should

be put together to be handled by the best-qualified professor. Naturally, the poorer teachers did not like this idea, for they would either lose their posts or would be made assistants to more capable men.

Those who were against fusion of the classes were in favor of simply having a loose union of the schools. This would put the colleges under one ruling body, but would leave the classes separate as they had been before. The less able instructors would then be in less danger of finding themselves replaced.

The people of Aberdeen promptly entered the feud between the Fusionists and the Unionists, as the two groups were called. The townspeople mostly took the side of the Unionists. The public and the newspapers in Aberdeen were continually trying to say how the colleges should be run. Since they found it easier to dictate to the poorer professors than to the good ones as a rule, they naturally did not approve of fusion. Besides, the people of Aberdeen also knew that the less able instructors would stay on for less money, and, in general, they were more interested in being economical than in improving standards of education.

Maxwell was a Fusionist. He was interested in having a university that would provide the best available faculty. Also, even though he was not one of the great teachers of his day, he was beyond doubt one of the most intelligent men in the country. Consequently, Maxwell was always highly thought of among the capable faculty members; and certainly he was one who

did not take his orders from the townspeople or the newspapers.

While the battle raged, Maxwell went on with his various researches as well as with his classwork. He also carried on a large correspondence. Although he had not yet met the great Michael Faraday, they exchanged letters, ideas, and scientific papers regularly. This doubtless kept them working along similar lines much of the time.

In Aberdeen, however, Maxwell did not find many men with whom he could exchange ideas easily. For one thing, the two colleges of the city had not attracted many exceptional instructors. However, the Principal of Marischal, Dr. Dewar, was one man with whom Maxwell could enjoy an intelligent conversation. Moreover, the whole Dewar family liked James Clerk Maxwell. He was invited to their home regularly, and even took a brief vacation with them.

The more he was with the Dewars, the more interested he became in the Principal's daughter, Katherine. His visits to the Dewar home became less and less for the purpose of conversing with the Principal. Instead, he spent more and more hours talking of Glenlair with Katherine. She was interested in gardening, and he enjoyed telling her about the beautiful gardens on his country estate. In February of 1858, they announced their engagement.

The wedding was small and quiet. Maxwell's closest friend, Lewis Campbell, made the trip to Aberdeen from

Oxford for the ceremony. He had just been married the month before himself, and Maxwell had journeyed south to be his best man.

Meanwhile the college situation in Aberdeen grew worse. While some professors became more friendly with the townspeople in the hope of holding their jobs, Maxwell continued to go his independent way. He was encouraged by the fact that upperclassmen and graduate students, who had reached a level at which they could choose their professors, voluntarily came to him. This was due partly to his being so likable, but it also shows that he was becoming a better teacher. Students were able to understand more and more of what he said.

The fusion of the schools came about in 1860. This meant that the townspeople had lost in their efforts to keep a lot of overlapping classes with low-paid teachers. It did not mean, unfortunately, that they lost their influence in running school affairs. As a consequence, the natural philosophy professor at King's College, who had been in Aberdeen far longer than Maxwell and who had a wide circle of friends in town, was given the natural philosophy post. Thus Maxwell found himself unemployed at the age of twenty-eight.

Next, he applied for a certain position at the University of Edinburgh; however, this happened to go to a close friend of his. Later, he applied for the professorship of natural philosophy at King's College in London. In the summer of 1860, he received an appointment there. Doubtless this was a good thing for Maxwell, be-

cause the outlets for his ideas in London were far greater than at Aberdeen or even Edinburgh.

Soon after moving to London, Maxwell met Michael Faraday. Their friendship became closer than ever. Faraday, of course, was no longer able to work as hard as he had previously. He was forty years older than Maxwell and had recently suffered a breakdown from overwork.

These two men came to understand each other better than most other men understood either one of them. Their researches continued to run along similar lines, with Maxwell finding the mathematical proofs for Faraday's theories.

The work at King's College was more demanding than that at Marischal had been. The school year was longer, and professors were expected to lecture to more classes. Also, evening classes for workingmen were considered an obligation rather than something one did if one wanted to.

However, this increased teaching load did not seem to burden Maxwell. He prepared each lecture carefully. At the same time, he enjoyed one of the most productive periods of his life as far as his own researches were concerned. His biggest difficulty was in finding time to write up his experiments and discoveries.

Soon after Maxwell's arrival in London, the British Association for the Advancement of Science met at Oxford, in June of 1860. He attended this meeting and showed his color box to the members present. This was well received, and it was agreed that it had advantages

over his color top, which he had shown to the Association previously, in Glasgow in 1855.

Maxwell took with him at the same time a paper on a new field of research. He had been preparing it for some time, and now he brought it to the attention of some members of the Association. It was about Daniel Bernoulli's theory of gases.

Bernoulli, a brilliant Swiss scientist, proposed the theory that gases were made up of separate particles that were moving independently among one another, except when they collided. The ease with which a gas could spread or flow helped Maxwell show that this theory was correct. He experimented with gases as conductors of heat and was able to gather additional proof. Turning to mathematics, he was able to estimate that each particle in a gas at room temperature probably collides with others about 8,000,000,000 times a second.

Later, Maxwell was to go much farther with his ideas on the motions of particles. But now his time was divided between this and his growing interest in electricity and magnetism. Now that he was personally in touch with Faraday, these fields held his attention.

Maxwell had less time to work with his color box than before, but he did not set it aside entirely. Instead, he turned it over to Katherine Maxwell. She was as fascinated by it as he had long been. Sometimes they worked with it together, and in this way Katherine Clerk Maxwell helped her husband to make a remarkable discovery.

The observations that Mrs. Maxwell made always differed slightly from those that Maxwell himself made.

At first, he suspected this was due to her lack of scientific training. Continued experiments, however, showed there was a pattern to the differences in the colors that each of them saw. They studied each other's eyes to see how their eyes differed. His were dark. Hers were light. This led them to suspect that people with dark eyes see colors a bit differently from those with lighter eyes.

Not only did Maxwell have dark eyes, but the coloring of his skin and hair was darker than his wife's. Katherine was very fair and had blond hair. This made the Maxwells wonder if people with dark eyes and dark coloring always see colors a bit differently from people with light eyes and fair coloring. They began to experiment with dark and fair people, asking them to study the spectrum in the color box.

Maxwell and his wife did not tell their friends what to look for in the color box. Thus, it was possible for them to discover that people with dark eyes and dark coloring almost always saw colors in the way that Maxwell saw them, while fair people reported colors that were close to those seen by Katherine. Although eye doctors insisted that these people had the same vision, Maxwell was in time able to announce that they did not. The way in which they perceived colors was not the same. A blue color that appeared a trifle on the pinkish side to one person might seem clearly blue to someone else.

The Maxwells found a pleasant home in the section of London known as Kensington. The best feature of the

house was its long, empty attic in which Maxwell could carry on his experiments. Very soon the neighbors began to suspect that they had a crazy man living next to them, for they thought they saw him at his attic window staring into a coffin for "hours at a time." Actually, Maxwell was working with his color box, which, at that time, was one about eight feet long.

Nor were these all the weird doings at 8 Palace Gardens Terrace, Kensington. In the heat of summer, the Maxwells had a raging fire in a stove in the attic. On this stove they boiled tub after tub of water as well as other liquids. Mrs. Maxwell tended the stove, keeping it red hot, while her husband bent over the steaming tubs. From time to time one or the other would stagger to the window for a breath of fresh air, where the neighbors would glimpse a perspiration-streaked face and a damp mop of hair.

At this time Maxwell was continuing his work on Bernoulli's theory of gases. The steam from the tubs was the gas that he was putting to various tests. He was studying how rapidly heat moved through the gases and how quickly they cooled in the absence of heat. He was also checking his own estimates that the particles in a gas collided 8,000,000,000 times a second. In addition, he wanted to know more about how gases flowed and what kept them from flowing.

Toward the end of the summer of 1860, the Maxwells went home to Glenlair. Maxwell wanted to be sure everything was in order before he started the fall session

Maxwell and his wife carried out experiments with gases in the attic of their home.

at King's College. Feeling feverish one evening, he went to bed early, expecting to feel all right in the morning. The next day, however, he ached all over and did not have the strength to get out of bed.

Katherine Clerk Maxwell immediately sent for a doctor. After he had examined the patient, the physician announced, to everyone's horror, that Maxwell had smallpox. The servants at Glenlair were so frightened they were ready to leave. Smallpox was a much feared disease in Maxwell's time for it killed many of the people who caught it.

Katherine, however, promised the servants that they would not have to enter the sickroom. This meant that she herself had to stay in the room and look after her husband. The servants would only come to the door with food and bedding; after they were gone she would open the door and take the things inside.

Throughout their happy life together, Katherine Clerk Maxwell helped her husband with his work in many ways. But her greatest contribution to science was saving her husband's life during this illness. Without her constant attention, it is believed that the scientist would have died.

After Maxwell had recovered, he and Katherine returned to Kensington. Gradually the neighbors got to know the Maxwells better, and they no longer seemed so peculiar. When Maxwell learned that anyone was sick in the vicinity, he would take time from his work to visit that person. He soon became popular, especially

with the children, for he had a spirited horse with which he could perform riding tricks.

In November of 1860, Maxwell was awarded the Rumford Medal. This was a high honor given by the Royal Society for scientific achievement, and Maxwell received it for his discoveries concerning color vision. Now, however, medals and prizes did not excite him as they had when he was younger. He had come to realize that the important thing was to increase man's knowledge rather than to seek his praise.

To scientific men, Maxwell had become well known by the early 1850's. To the general public, however, he was not as well known as other men who had accomplished less. In part, this was due to the difficult ways in which he expressed his theories. Also, many of the fields in which he worked did not produce colorful results that attracted public attention.

Because of his first lecture before the Royal Institution, however, Maxwell's fame increased. Faraday was probably influential in arranging for this lecture, which was given on May 17, 1861. His address was titled "On the Theory of the Three Primary Colors."

Maxwell did not become a frequent speaker at the Royal Institution, however, for his talks were sometimes too complex for even Royal Society members to understand thoroughly. Actually, Maxwell made a better impression with his published papers. Other scientists could then sit down with these reports and read them over and over if necessary.

When the British Association met at Manchester in 1861, the members decided that a committee should be formed to set up standards of measuring electrical resistance. The unit of electrical resistance is the *ohm.* It was named for Georg Simon Ohm, a German physicist, who had discovered a law for determining electrical resistance. This law, known as *Ohm's law,* explained how resistance to the flow of electricity in a circuit helps to influence the amount of electricity that will flow past a given point in a certain period of time.

It had become obvious to scientists, however, that the ohm was not the same unit to all scientists. Therefore, the committee was established to find a specific unit. Maxwell did not serve on this first committee. The members of it, however, ran into so many difficulties that they were unable to complete their work. Another committee was set up in 1862, and this time Maxwell was called on to lend a hand.

Much of the work that followed was under his supervision, and in 1863 the British Association ohm was announced. After this, one British scientist could talk of ohms with another British scientist and they would be speaking about the same unit of resistance. Maxwell felt that this achievement was highly important, because he was always in favor of developments that helped scientific men to understand one another. For this reason, he thereafter used much of his time in helping to find precise measurements—not only in electricity but also in the field of mechanics.

Although he enjoyed working with the young men who came to his lectures, Maxwell began to wish that he had more time for his own researches. Even though he regularly published papers during the years that he was in London, he could not find the time to write nearly all those that were taking shape in his mind.

Each summer the Maxwells went home to Glenlair. There, where life was peaceful and unhurried, Maxwell could concentrate on some of the writing that he could not find time for during the school year. Nevertheless, there were always distractions. Perhaps the Lewis Campbells or other friends would come for a visit. Since travel was difficult in those days, people did not go to Glenlair for an afternoon or a weekend. They went for a week or a month.

The morning hours suited Maxwell best for working. When friends kept him from accomplishing anything in the morning, however, he would stay up late at night, after everyone else was asleep, and make up for the time he had lost.

For relaxation at Glenlair, Maxwell went riding, and in September of 1865 he was trying out a new horse that he had just purchased. The horse and Maxwell were not used to each other. The animal broke into a fast run, and Maxwell gave him his head to let him use up his energy. Although he was an expert horseman, Maxwell unfortunately did not see a low limb sagging across the path down which the horse was racing. The bough struck him across the forehead.

Somehow Maxwell kept his seat and rode the animal back to the house. By the time he got there, his forehead was smeared with dirt and blood. He was a frightful sight to see, but Katherine was not easily frightened. She made him lie down at once, and then cleaned his wound.

Next morning when she changed the bandage, the cut did not look good to her. Maxwell would not let her call a doctor. He tried to work, but his forehead smarted so that he could not concentrate. The next night he tore the bandage from his head in his sleep, and before morning he was tossing fitfully.

When the doctor arrived, he discovered that Maxwell had erysipelas, or "St. Anthony's fire," an infection of the skin that caused a feverish illness. Maxwell was almost out of his mind from the terrible burning sensation; there was no chance for him to work now. Day and night Katherine sat by his bed, caring for him and reading to him.

Several days later, when he was feeling better, Maxwell began to worry about all the time he had lost. Through his mind ran the many ideas on which he wanted to do research or write papers. It began to look as though he would never find time to do all that he wanted to do.

There was one solution, however. If he did not have to hold classes at King's College, he would have the time for his own work. And, by living the year round at Glenlair, he could keep expenses down enough so that he would not need to teach.

Thus, to give himself the time he needed, Maxwell resigned the professorship of natural philosophy at King's College after five years of teaching there. He and Katherine gave up the house in Kensington and settled down to work at Glenlair.

9

The Pursuit of Invisible Particles

MAXWELL'S INCREASED leisure at Glenlair began almost immediately to show results. Although he had already published papers on the movements of gas particles, he could now develop his ideas on gases more completely. In 1866, he published a paper called *On the Viscosity or Internal Friction of Air and Other Gases* in the Royal Society's *Philosophical Transactions*. This paper and those that he had read to scientific groups before 1866 covered most of his theories about gases.

The theory of viscosity says that when a gas has a tendency to flow, or move, forces arise within the gas to prevent that flow. When Maxwell and his wife were working with steam in their Kensington house attic, they were investigating the flow of gases together with the forces that oppose the flow. The 8,000,000,000 collisions a second that one particle had with others, according to Maxwell's calculations, were forces opposing the flow.

Maxwell was not content with knowing how many collisions each particle of gas had with others; he also wanted to know how far each particle would travel after hitting one particle and before striking another one. He called this distance the "mean length of path which a particle describes between two successive collisions."

Certain facts that he already knew made him sure that he could work out equations that would give him this distance. One of these was the number of collisions a particle had in a second, which, he said, was a measure of the "internal friction of gases." In the attic at Kensington he had also studied "the conduction of heat through a gas," and he had been working at the same time on the rate at which one gas will mix with another —that is, "diffusion of one gas through another." The collisions per second, the rate at which a gas carried heat, and the rate at which gases mixed, he thought, would help him discover the length of a particle's path.

Before he started to develop equations for this, Maxwell tried to imagine some sort of mechanical system by

which he could express the actions of the particles of a gas. As a result, he began to imagine a system made up of small, hard spheres that were "perfectly elastic." By perfectly elastic he meant that after each collision they returned to the exact size and shape that they had been before the collision. He also imagined that they were "acting on one another only during impact." If he could show that such a system of spheres would act in the same way that gases were known to behave, he could then work out equations that would apply to both such a system and to gases as well.

As Maxwell pictured this system of spheres in his mind, however, he realized that other scientists would find fault with it. They would object that particles of a gas are probably not perfectly elastic so that after collisions they do not return to exactly the size and shape they were before. Critics would also point out that Maxwell's own work on lines of force indicated that the particles of gas had to influence one another at all times instead of just during impact.

To offset these arguments, Maxwell looked at the system of spheres in still another way. He said they could be thought of as "centers of force." The action of one on another would be too small to be noticeable *until* the two particles came close together. When they were almost together, however, one center of force would repel the other with a very powerful push. In this case, there would be no actual collision, and so the particles would not have to be perfectly elastic. Having thus attempted to ward off criticism of his system, Max-

well returned to the elastic spheres because he found it easier to apply equations to them than to centers of force.

Maxwell found the experiments of Thomas Graham, a Scottish chemist who had done much work with gases in closed containers, extremely helpful. Graham had worked with introgen and carbon dioxide. In certain experiments he had the gases in separate containers that were connected by a thin tube. In others he had used containers connected by a porous plug—a stopper with extremely tiny holes, or pores, through it. By relying on what Graham had done, Maxwell did not have to do much experimenting to learn how rapidly one gas could pass from one container into another.

With what his own experiments had shown him and with the knowledge of what Graham had done, Maxwell finally concluded that a particle of gas had a mean length of path 1/447,000 of an inch. But even before other scientists had a chance to find fault with him, Maxwell decided that his system of spheres must be discarded. In certain ways the system did not agree with the behavior of gases. For instance, the *specific heat* that his system gave for gases did not check with actual figures that had been worked out by the experiments of other men. The specific heat of a gas is a comparison of the amount of heat needed to raise the temperature of it one degree with the amount of heat needed to raise a certain amount of water one degree.

Indeed, critics did attack his work, just as Maxwell had known they would. Rudolf Clausius, a German

physicist, went into considerable research on the matter and was able to show where Maxwell had made some errors. Instead of being angered, Maxwell was pleased that other scientists were paying such close attention to his efforts.

Maxwell, in turn, studied the paper that Clausius wrote on the motion of particles. In some cases he agreed that the other scientist was right, and in time he was able to publish revisions of his own equations and theories, making use of the work of Clausius. In later papers he dropped the hard, elastic spheres and concentrated his attention on the ability that particles had to repel one another.

Even while other scientists were finding fault with him, they generously admitted that Maxwell's work on gaseous particles was of major importance. For one thing, seeing the particles as spheres gave support to a very important theory of science—the *molecular theory*.

For centuries, scientists had wondered what matter—anything which occupies space and has weight—was made of. For example, they asked themselves if a drop of water could be divided in two again and again and again and still be a drop of water. Finally, Democritus of ancient Greece developed a theory that everything is made up of tiny particles called atoms. *Atom* meant a particle that could no longer be divided. His idea, however, was not widely accepted. Since no one could see his particles, people found it difficult to believe in them.

From time to time down through the centuries, however, other scientists agreed with Democritus and they called the smallest particle of a substance a *molecule*. Daniel Bernoulli, the scientist whose work had caused Maxwell to become interested in the movement of gases, had agreed with Democritus, and he gave proof showing that particles existed. He said that the fact that gases were made up of small particles constantly in motion explained why gases could exert pressure. He published his theory in 1738.

John Herapath, an English scientist, carried Bernoulli's theory a step farther. In 1847 he published a book, *Mathematical Physics*, in which he pointed out that the motion of a gas depends on its temperature and the pressures exerted on it. If the gas were not made up of particles that were free to move, heat would not make the gas as a whole move more rapidly. Applying pressure to the gas would not cause it to become more agitated.

When Maxwell developed his system of spheres, he was agreeing with Bernoulli and Herapath. He, too, was saying that everything is made up of molecules.

Maxwell's work on gases was important in other ways as well. Before he started investigating gases, most scientists who believed in the theory of molecules had assumed that all the particles in a gas were moving exactly alike. This meant that they all moved with the same velocity.

Maxwell compared the movement of particles in a gas to the people in a crowd. If one could look down on

a very large number of people moving along a street, he would discover that each person had a movement of his own. Some people would be hurrying and some people would be going slowly. Frequently there would be collisions. These collisions would cause people to change their speeds. Some of the ones who were hurrying would be forced to slow down, while those who were poking along would be driven into moving faster. However, the general flow of the crowd, or its over-all velocity, would not change. The amount that some people speeded up would be balanced by the amount that others slowed down. Thus, the crowd would continue to move along the street at the same rate of speed.

Moreover, said Maxwell, the crowd would not contain the same individuals at all times. Some would cross the street or disappear into stores. But they would be replaced by others coming from across the street and coming out of stores. Therefore, the size of the mob would not really change.

Maxwell pointed out that the particles in a gas were like the people in a crowd. Their velocities would change as they bumped into one another. And no particle would necessarily remain in one general region. It might move anywhere within the area of the gas. But it would be replaced by another molecule coming from another spot, so the density of the gas would remain the same.

Before Maxwell described gases in this way, earlier investigators had tried to picture how one particle alone would behave. These men had attempted to trace the

history of this particle, and their method of investigation is known as the *historical method.*

But because Maxwell dealt with the statistics—collected and classified facts—of a group of particles rather than with an individual one, he called his method of investigation the *statistical method.* His introduction of this new method was a major contribution to molecular physics, which is the study of the particles, or molecules, of matter.

Because Maxwell compared molecules to crowds of people, a friend of his thought it very amusing once when he saw Maxwell himself caught in a crowd. The friend was coming down the stairs at the Royal Institution after a lecture. In the main lobby below he saw Maxwell stuck in the crush of people trying to leave the lecture hall.

"Hello, Maxwell," the friend called, "can't you get out? Surely, if any man can find his way through a crowd it should be you."

The statistical method helped Maxwell to do more than simply prove that the molecules in a gas would have varying velocities. It also indicated to him that the particles could not possibly follow uniform paths. The collisions would send them off at a variety of angles.

A stream of water may squirt from a hose with all the drops going in the same direction. But as soon as they strike something, they splash away to every side. A stream of particles in a gas would do the same thing, so very shortly there would be no stream at all. There would be a mass of particles shooting around in all direc-

tions as continued collisions kept their paths constantly changing.

Moreover, since all experiments indicated that particles in a gas moved in straight lines—changing their directions only when they collided with other particles—Maxwell and other scientists said that the pressure a gas exerted on the sides of a container was due to the impact of particles against the container's sides.

From what they knew about gas particles, scientists developed what they called the *kinetic theory of gases.* The word "kinetic" comes from a Greek word meaning "to move." And the theory was called the kinetic theory because it was based on the movement of the particles making up gases. The theory said that the particles move in straight lines, they change their velocities upon contact with other particles, and they exert pressure through colliding with the sides of a container.

The kinetic theory helped Maxwell to reason that two different gases in containers of equal size and kept at the same temperature would exert the same pressure only if they were made up of the same number of molecules. Since the pressure exerted would be the result of the number of collisions, they would have to have the same number of molecules to bring about an equal number of impacts. Amadeo Avogadro of Italy had already announced this idea many years before, but Maxwell's support of the theory caused more scientists to believe in it.

To test the pressures of gases, Maxwell built a container that had two compartments. One compartment

was exactly the same size as the other. The partition that separated them was a thin membrane that would bend easily. When he put a gas in one half of the container, the membrane would bulge into the other half. Then he would put a gas into the second half. As more gas flowed into the second half, it would push the membrane back.

By carefully adjusting the amounts of the gases, Maxwell could get the membrane so that it was exactly in the center of the container. When he reached this state of *equilibrium*, or balance, he knew that the gases were exerting the same pressure on the membrane. This told him that he had approximately the same number of molecules of gas in each half of the container.

One gas, however, might appear to be very "thick," while the other appeared "thin." Maxwell was then able to announce that molecules vary in size. Thus a "thick" gas was made up of larger particles than a "thin" one.

Scientists came to express this by saying that the "thick" gas was more *dense* than the other. The relationship of the density of one gas to another was called its *specific gravity*. That is, it was specifically, or exactly, a certain amount denser than another gas with which it was being compared. When they took one gas, such as hydrogen or air, and compared all other gases to it, they had a table of related specific gravities.

If the membrane in Maxwell's chamber was punctured with tiny holes, he found that the molecules of gases would fly through these holes. The two gases

would mix, or *diffuse*. The rate at which one gas would flow into the other would depend partly on the velocities of their molecules. Since molecules have varying speeds, the rate of diffusion would depend on the average of all their velocities.

The average velocity of the molecules of gas, however, could not be calculated simply from the speed with which a gas mixed with another gas. Many particles would strike molecules of the second gas and would bounce back. Not only did one gas have viscosity—opposing flow—within itself, it also had viscosity in diffusing with air or other gases. By judging the rate of diffusion of two gases and the force of viscosity keeping them apart, Maxwell could determine the average velocity of their molecules. Here again he relied somewhat on the work of Thomas Graham.

In their experiments, both Graham and Maxwell used gases of widely different specific gravities. Using a "thick" gas and a "thin" one, Maxwell would place them a distance apart and let them flow into an air space between them. Air is a mixture of gases, of course, so the forces of viscosity would be set up as the gases flowed into the air space. Since there were bigger molecules in the dense gas, they had more collisions and were driven back more than were those of the "thin" gas.

Since the bigger molecules were driven back more often, the particles of the "thick" gas did not advance any more rapidly than the particles of the "thin" gas. In fact, Maxwell discovered that the two gases advanced

at the same rate. He was quite surprised. He had discovered that the rate of diffusion of gases did not depend on the density of the gases involved.

In another experiment, Maxwell hung three plates of glass in a large container. They were free to swing between other plates of glass that were held fast. A gas was put into the chambers of this container, and the three plates were set to swinging.

The viscosity of the gas, or its natural resistance to being moved around by the swinging glass plates, would eventually bring the plates to a stop. Maxwell could see how long it took the gas to stop the plates, and then he could use another gas and see how long it took. This was another way in which he calculated the viscosity of different gases. He discovered, for example, that dry air is more viscous than damp air. And further, he found that any form of air is more viscous than hydrogen and carbon dioxide.

Maxwell thought that by putting different amounts of the same gas in the chamber at different times, he could learn how much influence pressure had on viscosity. The more of a gas he put in, the greater the pressure would be, for there would be more molecules of gas to strike against the glass plates and to make them stop moving. To his surprise, a larger amount of the gas had no effect on the plates. Although there were more particles of the gas, their average velocity was not changed enough to make a difference in viscosity. When Maxwell heated the gas, on the other hand, the molecules stopped the plates more quickly because they moved

around faster and had more impacts on the plates of glass.

Some scientists at this time were convinced that gases mix slowly because they are really not made up of little particles; in other words, they did not believe in the molecular theory. Maxwell was able to use his statistical method to show that these men were in error. To prove his point, he pictured two coasting trains passing each other on tracks that are side by side. If a man jumps from one train onto the second, he has momentum—that is, a quantity or amount of motion—in the direction that the first train is going. His momentum depends on the speed of the first train and is, of course, opposite to the direction of the second train. Consequently, he slows down the second train slightly by the force of his momentum.

Now, if many people on both trains started jumping back and forth, their combined momentums would slow the trains more and more. Finally, the trains would cease to move.

In the same way, collisions of molecules of gases that are mixing will slow down the rate of diffusion. Therefore, instead of harming Maxwell's molecular theory of gases, the slowness of diffusion strengthened it.

As he continued to work on the diffusion of gases, Maxwell became more dissatisfied with some of his earlier work in the field. Once more he set out, using the corrections that Clausius had made in his earlier equations, to find the mean free path of molecules of gases. For hydrogen, he found that a particle had an average unopposed path of 1/250,000 of an inch before a col-

lision. For air, he discovered that a molecule could probably hope to move freely for about 1/389,000 of an inch. The other gases that were available to him at that time fell between these two figures. Even so, he was still not allowed the final word on this subject, for today these figures have been corrected slightly because of experiments using modern laboratory methods. The important thing was that Maxwell was interested in testing his own opinions, as well as those of other men. He was not afraid to admit that he sometimes made errors.

Another field of experimentation with molecules was concerned with the attraction between bodies. The attraction between molecules was what scientists particularly wanted to find out more about. Because Maxwell agreed with Faraday that all objects attracted or repelled all other objects, he was very interested in testing the attraction between molecules. Although he could not hope to do all the work that there was to be done in this field, he did succeed in interpreting the results of others so that they made sense.

It was found, for example, that the molecules of a gas that was not under great pressure did not exhibit much attraction for one another. Apparently they were too far apart in relation to their very small size to exert much attractive force. As the gas was squeezed tighter and tighter, however, the particles began to attract one another more readily. Experimenters could tell this because it became easier for them to squeeze, or compress, the gas. Obviously, when the particles were driven close together, their forces of attraction did not have to

reach out over as much space as before to meet one another.

Theoretically, if this attraction continued, a gas would eventually be squeezed down to where it seemed to be a tiny solid lump. This did not happen, however. The distance at which the molecules would attract came to an end; then the particles began to repel one another. This repulsion of the particles then increased quite rapidly until at last a gas could be squeezed no smaller.

Maxwell was then able to state, "no attainable force can reduce the distance of the particles to zero." In other words, he was saying that there would always be some amount of space between the molecules of a gas. They would never stick together and become a lump, so a gas would always remain a gas in spite of all the forces that could be used to try to compress it into a solid. This, of course, did not mean that a gas could not be turned into a solid by lowering its temperature.

In performing this valuable work with gases—and with solids, too—James Clerk Maxwell was rapidly becoming known as a leading scientist in the field of *molecular physics*, as the study of molecules is called.

10

The Greatest Discovery of All

ALTHOUGH James Clerk Maxwell had given up teaching in order to have more time for his own research and writing, he did not cut himself off from college life altogether. He was well aware of what was being taught at Cambridge and other schools, and it worried him that the courses at Cambridge were becoming out of date. He let the officials at Cambridge know how he felt. The officials themselves could see that the new dis-

coveries of men like Maxwell were making it necessary to revise old courses or to institute completely new courses of study.

Appropriately, the officials called on Maxwell himself to help plan some of the changes that were needed. Although Maxwell did not return to Cambridge to lecture, he did lend a hand in revising these science programs. Maxwell also went down to Cambridge almost every spring to help examine the graduating students. This was work that he enjoyed for, although it took him away from his own scientific inquiries, it kept him in touch with young people.

Despite the attention he was getting due to his papers on gases and color vision, Maxwell felt that he should visit other scientists and learn more about what they were doing. Possibly he had been influenced by some of Faraday's stories about a trip he had taken to the Continent as a young man. In any case, Maxwell wanted to see more of Europe, so he and Katherine set out in the spring of 1867. Much of their time was spent in Italy, but they also visited Germany, France, and Holland. In these nations were some of the most advanced laboratories of the world where brilliant men were working to learn more about physics, chemistry, and mathematics.

At Marseilles, France, the harbor officials discovered that the ship carrying the Maxwells had some sick people aboard. No one was permitted to land, and the ship was quarantined for days. This was an emergency that vessels were not equipped to handle in the 1860's.

There was no trained medical staff aboard to look after those who were sick.

Maxwell, however, threw himself into the work of looking after those who were ailing. Some days he was hardly more than a water boy or a chambermaid; Katherine helped, too, for she had had valuable experience in nursing her husband through two serious illnesses. At last the patients recovered, and the vessel was allowed to dock.

After nearly a year and a half in Europe, the Maxwells returned to Glenlair. The mathematician had had the chance to meet many prominent scientists and to see the best laboratories Europe had to offer. Having absorbed much, he was now ready to settle down to his own work once more.

Regardless of how important scientists rank Maxwell's work in color vision and molecular physics, most are agreed that these fall below the magnitude of one other achievement. This was Maxwell's development of a theory of electromagnetism.

It cannot be said, of course, that Maxwell started developing his ideas on electricity and magnetism after he returned from the Continent in 1868; actually, he had been thinking them through for many years. Just as his work on Saturn's rings, color vision, and molecular physics had all been woven in together, he had also been thinking a great deal about electricity and magnetism at the same time. In fact, his work on molecules helped him to develop his theory of electromagnetism.

Another influence was the paper he had written previously about Faraday's lines of force.

As is almost always the case with scientific discoveries, the work of earlier men had paved the way for Maxwell's work.

Faraday, for example, repeated some of the work the earlier English scientist Henry Cavendish had already done on electrically charged bodies. He went further than Cavendish, however, in trying to find out how it was possible for charged objects to attract or repel each other.

Mathematicians, Faraday knew, claimed that objects could attract or repel because it was possible to have "direct action at a distance." That is, a charged body in one location could influence a charged body at another with no visible form of connection between them. Faraday questioned this. He felt that there had to be *some* medium between the two bodies to carry the force of attraction or repulsion. For instance, direct action at a distance, he reasoned, could not explain why an electric current in a wire could affect iron filings sprinkled on a paper held a little above the wire. Action at a distance might push the filings away or pull them closer if they were near a magnet, but how could it make them form into definite lines? In fact, how could direct action turn magnetic action into electricity or electric current into a magnetic action?

Cavendish had been a student at Cambridge, and it was there that Maxwell learned of his notes and had a chance to study them. He also read everything that Fara-

day had written; the more he thought about the works of these two men, the more he felt that mathematicians were wrong about direct action at a distance. Although Maxwell was a mathematician himself, he began to believe that there was *something* that transmitted, or carried, the attractive or the repulsive force.

As he tried to picture such a medium in his imagination, Maxwell began to visualize a system of vortices. *Vortices* are whirlpools, and Maxwell could picture the universe consisting of extremely small vortices that were actually just whirling points. He called them *molecular vortices* since he believed that everything was made up of molecules. Moreover, all of them would be whirling alike.

In testing his theory of molecular vortices in his mind, he thought of it first in connection with magnetism. To do so, he returned once more to Faraday's lines of force; he said the vortices were tiny cylinders rotating around these lines. As the vortices whirled, they would have tension in the direction of the lines of force—that is, just as whirlpools draw floating objects down through their centers, the vortices would have an ability to draw (a tension) where they rotated around the lines.

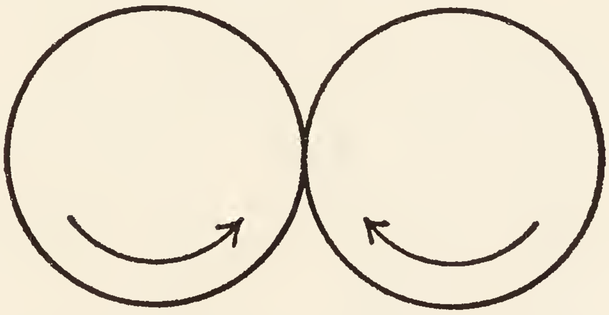
This could explain a magnetic attraction to Maxwell, but it was not enough to tell him why some substances, such as iron, could produce a strong magnetic force and others could not. As he considered his whirling points, however, another idea came to him. All whirling bodies exhibit centrifugal force, as he had pointed out when writing about Saturn's rings. Therefore, there would be

a force at the surface of each of the vortices. Since different substances have different densities, it would be only logical to assume that the vortices in different substances would also have different densities. And Maxwell concluded that the vortices of any one substance would whirl at a rate related to their density. In other words, the velocity of any particular vortex would depend on the substance of which it was made. Reasoning thus, he was able to imagine that the velocity of the circumference of each vortex determined the intensity of the magnetic force of that vortex; and the magnetic force that a substance could exhibit was the sum total of the intensities of its vortices.

Up to this point, Maxwell's theory was primarily one of magnetism, yet he was certain that it could also be made to apply to electricity; thereby, it would become a combined theory of electromagnetism. What made him so sure of the relationship between magnetism and electricity was the work Cavendish, Oersted, and Faraday had done which proved direct associations between the two. However, when he applied his vortices to an electric current, he ran into trouble.

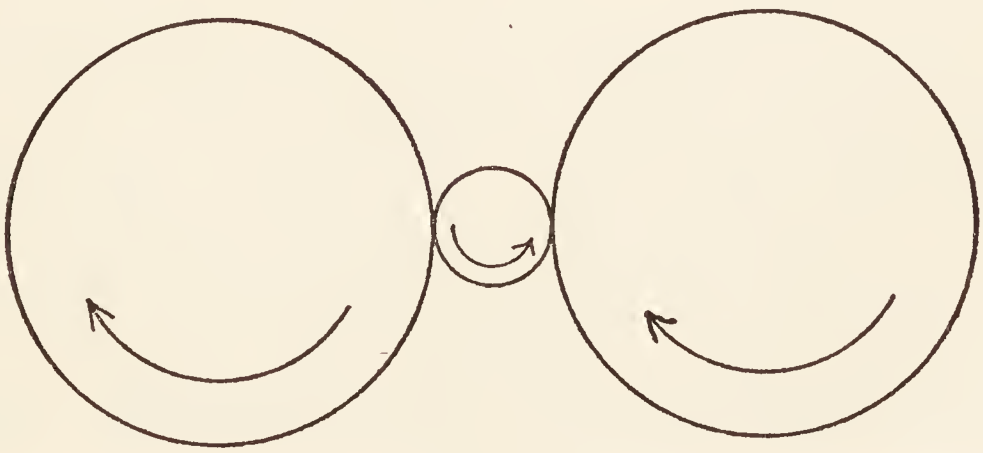
A magnetic force, Maxwell reasoned, is generally confined to a certain area, but a current of electricity can flow through miles of wire. For vortices to carry a current along over such a distance without the current's losing most of its force, the vortices would undoubtedly have to be touching one another. But if they touched, they could no longer all be whirling exactly alike, which he had previously stated was necessary.

To explain more clearly what the problem was, Maxwell pictured two wheels that had their rims touching. One wheel could be turned by turning the other—that is, the friction where they touched caused the second one to turn. It would, however, turn in the *opposite* direction from the one touching it, like this:



Since this was true, Maxwell did not see how his vortices could all be turning exactly alike; they could not all be turning in the same direction if they were touching. Puzzled, Maxwell now gave his system of vortices more careful thought.

In many machines, Maxwell knew, the same directional motion of one wheel is transferred to another by a little wheel in between. This little wheel goes in the opposite direction from the first wheel, but it turns the third wheel *in the same direction* as the first. This middle, or second, wheel Maxwell called an "idle wheel:"



Now, reasoned Maxwell, if his molecular vortices were the "main" wheels, why couldn't each be surrounded with smaller particles? These particles would be the "idle" wheels between the important ones. They and the vortices together would then make up the medium which Faraday had suggested must exist throughout the universe. As he thought about this, Maxwell realized that whatever the particles were, they *had* to account for the flow of electric current. Therefore, he said that they were particles of electricity.

When he originated this theory, Maxwell helped to explain much about electric currents that had not been understood before. For instance, scientists did not know why the magnetic field around a magnet, in itself, did not have the power to create an electric current, but that a change in that field—as Faraday had shown—*would* do so.

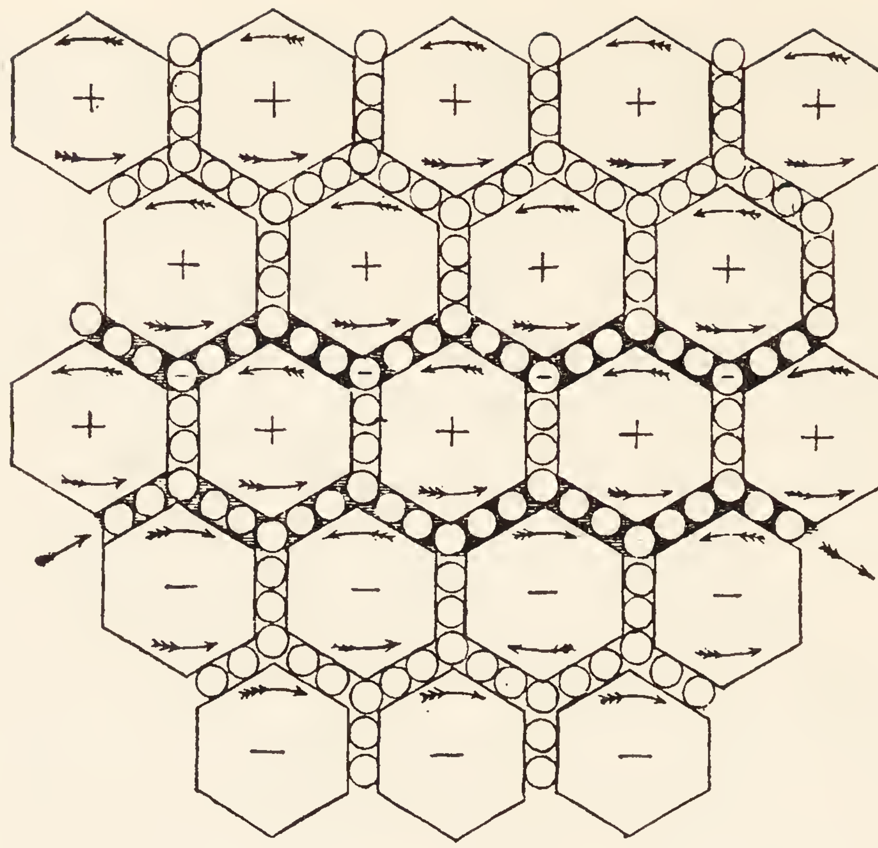
Maxwell said that in such an unchanging magnetic field, all of the vortices were spinning at the same speed as well as in the same direction. Therefore, all of the particles of electricity between them also spun at a constant speed. As long as they did so, they would tend to stay in one place.

But when the magnetic field was changed, the vortices would also undergo a change. And, since the main property of these vortices was rotation—spinning—it would be their rotation that would be altered. It would not be their direction that would change, for they would still have to whirl in the same way around the lines of force if they were to keep the magnetic qualities

that Maxwell had already found they exhibited. The ones touched first by the magnetic field as the field changed would go either faster or slower than they had been going before. Where these first ones touched particles of electricity, they would cause the particles to speed up or slow down as well. However, the next row of vortices would not yet be changing speed. They would still be going at the original velocity, and they would have a tendency to keep the particles from speeding up or slowing down. Now the particles would be torn between two speeds—that is, they would be put under great strain as they tried to speed up or slow down to match the velocities of the vortices on one side and at the same time tried to go at the old rate of speed exhibited by the vortices not yet affected by the change in the magnetic field.

The particles, now unable to whirl at one rate of speed, would be forced to move about, or flow, between the vortices. In other words, they would produce an electric current. An electric current then, according to Maxwell's theory, was caused by strains in the medium making up the universe. As soon as all of the vortices near the magnetic field had been affected by the change in that field, they would all have taken on the new speed, of course. Then the particles would no longer be torn between two speeds, they could remain easily in one place, and the current would cease to flow.

According to Maxwell's system, the individual particles could not touch each other, for this would create the same problem that he had had before he thought of



A sketch from Maxwell's papers. A magnetic disturbance, starting at the outside arrow on the left, forces the vortices (the large figures) to change their rate of rotation so that the particles of electricity (the small, round figures) are torn between vortices spinning at different velocities. As the particles try to turn at two different speeds, they move, creating a flow of electricity toward the right.

the particles—they would be trying to make one another turn in opposite directions. But if there was an infinitely small gap between particles, and if they kept the vortices from touching one another, then his system would explain magnetism and electricity. Because it involved both of these phenomena, Maxwell's theory of vortices and particles came to be called the *theory of electromagnetism.*

To explain why some materials would not carry an

electric current—that is, acted as insulators—Maxwell used the same theory of vortices and particles. He said the vortices of some materials were elastic. They would stretch when the particles of electricity between them were torn between two speeds of rotation. In fact, they would stretch enough to balance the force of the particles instead of letting them move along. This, he said, was actually the start of an electric current that never managed to flow because its force was balanced by the elasticity of the vortices. After the electricity was taken away, these elastic vortices would return to their normal shapes and sizes.

When the vortices in an insulator returned to their original position, they would do so as suddenly as the electric current was turned off. Because of this, they would for an instant overshoot the position they usually had, then shoot back, and in general vibrate about what were usually their normal positions. This vibrating would create for just an instant a wave motion through the insulator. Maxwell said this was a *displacement current*, or *wave*.

Two German scientists, Wilhelm Weber and Friedrich Kohlrausch, had already worked out the velocity with which electricity travels along a wire; Maxwell repeated their experiments and found that he agreed with them. He went further, however, and sought to learn if a displacement current traveled at the same speed. Since he said that displacement currents and electricity were both electromagnetic in character, there ought to be a close relationship between their velocities.

On the other hand, if displacement currents proceeded at much different velocities from electric currents, something was sure to be wrong with his theory of electromagnetism.

To test his theory and to find the velocity of displacement currents, Maxwell measured the force of attraction between two coils of wire carrying electric currents. He also measured the attraction between two metal disks that had been charged with electricity but that did not have currents flowing through them. By comparing the two attractions, he was able to work out a relationship that expressed the velocity of a displacement current—193,088 miles per second.

The figure that Weber and Kohlrausch had determined for an electric current was approximately 186,563 miles per second. Maxwell was delighted to see that displacement currents and electric currents traveled at velocities so nearly the same. In fact, the differences between the two figures could easily be accounted for by the fact that the equipment for calculating speeds could not be considered completely accurate. The velocities that he had found for electric currents were not exactly the same as the 186,563 miles per second the Germans had discovered, so he felt certain that his 193,088 miles per second for displacement currents proved that his theory of electromagnetism was sound.

Now Maxwell realized something even more exciting, at least to him. Scientists had long been working to determine the exact speed of light and a number of different estimates had been worked out. Maxwell, with

his remarkable memory, recalled that the most recent figure he had seen for the velocity of light in air was 195,647 miles per second. At the same time, he remembered that the figure most often accepted as being right was 186,000 miles per second. These figures were right in the neighborhood of his figures for the velocities of electric currents and displacement currents.

Other facts raced through Maxwell's mind at the same time. He knew that in 1845 Michael Faraday had succeeded in proving that magnetism could have an influence on light. Faraday had used an electromagnet to change a beam of polarized light. Putting all these facts together, Maxwell made a great addition to his electromagnetic theory. He stated that light must be electromagnetic in character, and his theory that light travels in electromagnetic waves is known as the *electromagnetic theory of light.*

Before Maxwell put forth his theory that light was electromagnetic in character, many scientists had said that it was a series of waves, or *undulations*—that is, light traveled in waves like those traveling across water when it is disturbed. But undulations could never explain very well why there were such phenomena as double refraction. Maxwell, on the other hand, said that since magnetism, electricity, and light were all electromagnetic in character, it was easy to imagine that there were many more kinds of electromagnetic action still not known. Light, therefore, did not have to be made up of just the colors that a simple prism produced. It could be *two* electromagnetic phenomena at once, each

of which could be broken down into separate spectrums.

This line of thinking carried Maxwell on to still another brilliant idea. Since double refraction showed that there was more than one spectrum, and since neither electricity nor magnetism could be seen, was it not more than likely that there were electromagnetic waves that had not yet been discovered? Perhaps the spectrum was just the section of light that man's eyes were able to detect. Yet wasn't it highly possible that there could be other electromagnetic waves—some faster, some slower—than those of the simple color spectrum? These would be waves that man could not see, but actually they would be a part of the spectrum.

The few men who followed and agreed with Maxwell's reasoning called such a total spectrum—light rays that could be seen and those that could not—the *electromagnetic spectrum.*

Maxwell used vortices and particles of electricity to explain his theories because they were objects that could be presented in a mechanical way and that other men could understand. He did not mean, however, that everything in the universe is made up of "wheels." Rather, he meant that throughout the universe there is an electromagnetic medium. He said that scientists should keep searching to find out what it is; in doing so they should keep in mind, as his vortices and particles indicated, that it is a "phenomenon of rotation."

Maxwell was asked to write an article on the "ether"—the name sometimes given to the electromagnetic

medium. In this article, he indicated that the "ether" might be just as artificial as some men claimed his vortices and particles were. It was evident that he thought of it as the electromagnetic medium, and he said it differed from other known media in that its movements *did not* produce heat.

Since ordinary wheels produce heat when turning against one another, Maxwell found it necessary to explain why his rotating vortices and particles did not make the world continually hot. Maxwell answered that it was absolutely necessary for his vortices and particles to move *without slipping*. It is the slipping, or friction, between wheels that causes them to get hot, but if his vortices and particles never slipped, or rubbed against each other, they would not heat up.

Electricity creates heat, however, when it flows through a wire. Maxwell also had an explanation for this. He said that, since all matter is made up of molecules, the vortices and the particles have to exist *within* molecules. The vortices are ever so much smaller than molecules, so there are many of them to each molecule. And, because the particles are yet smaller than the vortices, there are many, many of them to a molecule as well. Thus, when particles tried to move from one molecule to another they experienced resistance. This resistance caused them to acquire motions that did not correspond with the motions they already had, or "irregular motions," as Maxwell called them. These irregular motions constituted heat and accounted for the wasting of electrical energy in a wire.

As Maxwell's ideas on electromagnetism were brought forth during the 1860's, they met with little acceptance. His experiments did not actually prove that there were electromagnetic waves. They only proved that there might be. Moreover, most men felt that the velocities he had obtained for displacement currents and electric currents were not close enough to the velocity of light to prove a definite relationship. Besides, his formulas were exceedingly complex and even experienced scientists sometimes had trouble following them.

During his lifetime Maxwell was usually honored for his work in molecular physics and color vision. Nevertheless, a few of his students felt that he was on the right track in his electromagnetic theories and they continued to work along the lines he had established. In this way they helped to keep Maxwell's theories alive, even after Maxwell's death. Then, too, his ideas had spread to other countries.

In Germany, a young man named Heinrich Hertz took up the study of electricity and became interested in the electromagnetic theories. He was not yet ten years old when Maxwell published his first papers on electromagnetism, but after Maxwell's death Hertz somehow caught the enthusiasm that Maxwell had created in men who had studied directly under his supervision. Later, Heinrich Hertz was able to perform the experiments that definitely proved the existence of electromagnetic waves.

Hertz did his work between 1886 and 1889, when he was able to show that electromagnetic waves are long

waves that are vibrating at right angles to the direction in which they are traveling. He proved that they traveled at the velocity of light, and that they could be reflected, refracted, and polarized in the same way that light could. There could no longer be any doubt that Maxwell had discovered electromagnetism, even though it had taken someone else to make the world believe him. Unfortunately, Maxwell did not live to know of the proof that Hertz produced.

The work of Maxwell is often judged to be far greater than that of Hertz in this field, despite the fact that the waves are often called *Hertzian waves.* Maxwell had little to work on but a theory by Michael Faraday that magnetism, electricity, and light were all inter-related forms of energy. Simply by using his imagination, Maxwell could picture vortices and particles of electricity. And, what is still more remarkable, he could develop mathematical equations that indicated the relationships between electricity and light and showed how his vortices and particles worked.

It is difficult to imagine that a man could use pure mathematics to discover something that he could not find with experiments. Nevertheless, this is exactly what James Clerk Maxwell did, and his work in electromagnetism is his outstanding contribution to science.

11

Maxwell Returns to College Life

EVEN THOUGH Maxwell had helped to reorganize the science program at Cambridge, the University was still frequently criticized for being out of date. Many professors still gave their lectures as though nothing new were being discovered, despite the accomplishments of such scientists as Michael Faraday, Amadeo Avogadro, Joseph Henry and Maxwell himself. When Maxwell went to Cambridge each spring to help examine the graduating students, he could tell by the answers he re-

ceived that the students were not being given a chance to study recent developments in molecular physics, magnetism, and other fields.

Each time he visited the University, Maxwell pointed out that other schools would become more scientifically advanced if Cambridge did not make an effort to keep up to date. And in 1870, his complaints and those of other critics finally accomplished something. In that year the Duke of Devonshire, Chancellor of the University, donated the money to build a physics laboratory; early the following year a Professorship of Experimental Physics was established. The problem was to find a man qualified to fill this professorship and to guide the work of building and organizing the new physics department and laboratory, which was to be named for Henry Cavendish.

The first man to be considered was not James Clerk Maxwell, possibly because Maxwell's record as a professor had never equaled his other achievements. But this first man was not interested, and later the officials did approach the master of Glenlair.

Maxwell had been very comfortable on his estate during the six years after his retirement in 1865; he had enjoyed having the time to do his own research and writing. Consequently, he was at first reluctant to accept the responsibility of supervising the building of the Cavendish Laboratory. However, he had always liked to work with college students, and he was seriously concerned about their not being introduced to recent scientific developments.

Thus, he finally agreed to accept the Professorship of Experimental Physics at Cambridge. But before Maxwell and Katherine moved there they got the University to agree that Maxwell could retire to Glenlair again at the end of one year.

A year, however, was hardly enough time to establish a new department of physics, and the laboratory could not be completed that quickly. For these reasons, Maxwell felt that he had to stay on at Cambridge until the laboratory was finished. In the spring of 1874, he was satisfied to see the new building opened for experimental research. Even then, Maxwell did not feel that his work at Cambridge was over. His lectures were proving popular, and he had become better able to make scientific subjects clear.

In addition, by the time the laboratory was ready for use, Maxwell had already completed two of the major works that had occupied his time at Glenlair. In 1871, he published a textbook called *A Treatise on Heat.* Two years later his most important book, *A Treatise on Electricity and Magnetism*, was published. At the same time, he was well along with the writing of a book to cover his work on molecules and their motions; and he felt that he could carry this to completion without retiring to his country estate again. In 1876, he published this book, titled *Matter and Motion*, which he modestly called "a small book on a great subject." For many years it was the leading text in the field of molecular physics.

While he was having his own works published, it did not seem fair to Maxwell that the important work of

Henry Cavendish should continue to be so little known. Therefore, he set out to edit the Cavendish papers, and this project kept him busy until it appeared in print in 1879.

After he returned to Cambridge, Maxwell began to change rapidly in appearance and in manner. Close friends, such as Lewis Campbell, remarked on the fact that he seemed to change from a young man to an old man almost overnight. The once black hair had rapidly turned to gray.

Katherine, too, seemed to age rapidly, but the doctors understood the reason for this. She had become seriously ill, and there was no hope for her improvement. Just as she had cared for James, he now looked after her, sitting by her bedside all night even though he knew he had to lecture at the Cavendish Laboratory in the morning. His friends thought that this must be the reason for Maxwell's aging so quickly.

As it turned out, Maxwell was also ill, but no one realized it. He was a better nurse for Katherine than he was for himself. During the spring of 1877, he began to have trouble with his throat. One day at the laboratory he dissolved some soda in water and drank it; this lessened the pain in his throat, so he continued to do this for two years instead of going to a doctor.

At last, in 1879, Maxwell consulted a doctor, but by then it was too late. The disease was cancer, though the doctor possibly called it by some other name because little was known about cancer in those days. Knowing that he did not have long to live, Maxwell did not worry

about himself but set about making arrangements for someone to look after Katherine.

On November 5, 1879, it was obvious to everyone that Maxwell would not live through the day. As the hours passed, he grew weaker and weaker. Almost his last words were, "God help me! God help my wife!"

The funeral was held in Trinity College chapel in Cambridge, after which Maxwell's body was taken back to Scotland to the family cemetery at Glenlair. Katherine gave his library of science books to the Cavendish Laboratory. She herself was looked after by her husband's relatives and was made as comfortable as possible.

The first important recognition that Maxwell had received had been the Rumford Medal in 1860, for his investigations of color vision. After that, he was showered with honors; especially during the 1870's, he regularly received awards and other forms of recognition. He was given an honorary degree by the University of Edinburgh in 1870 and another by Oxford University in 1876. He accepted these and dozens of other honors quietly.

James Clerk Maxwell was not seeking fame. His goal was to understand and to make understandable the world of science.

12

The Importance of Electromagnetic Waves

HUMAN BEINGS have always made use of electromagnetic waves. There can be no seeing without them, for without light there can be no vision. However, the eyes are sensitive to only about three per cent of all the electromagnetic wavelengths. Even creatures that do not have eyes are sensitive in some way to certain kinds of the waves.

Even before Maxwell advanced the theory that such waves should exist, men were making use of them for other purposes besides vision. For instance, the short

ultraviolet rays in sunlight provided suntans; and the heat of the sun—provided by the long infrared rays—was often concentrated by means of a lens to start fires.

After the existence of electromagnetic waves had been proven by Hertz, men sought more knowledge of them, and it was discovered that they range in lengths from hundreds of miles down to less than a billionth of an inch. Maxwell had predicted that they would come in various lengths, although he probably did not foresee that they would have such a wide range.

The long ones, it was learned, could be used to carry sounds through space; as a consequence, radio was developed. Since radio waves, like light waves, can be reflected, scientists discovered that they could be bounced off certain layers of the earth's atmosphere. As a result, radio broadcasting can be carried on over great distances. In this age of man-made satellites, it has even been discovered that some waves can be sent up through the atmosphere to reach objects far out in space. When men finally establish bases on the moon, it will be possible to communicate with them because of the extremely long electromagnetic waves that will either be sent directly to the moon or will be transmitted onto the moon from low-orbiting space stations.

A more recent development, which is related to radio, is television. Not only sounds but pictures can be transmitted at a distance because of electromagnetic waves. Just as the waves that make radio possible are called radio waves (they are also the ones known as Hertzian waves), those that make television images pos-

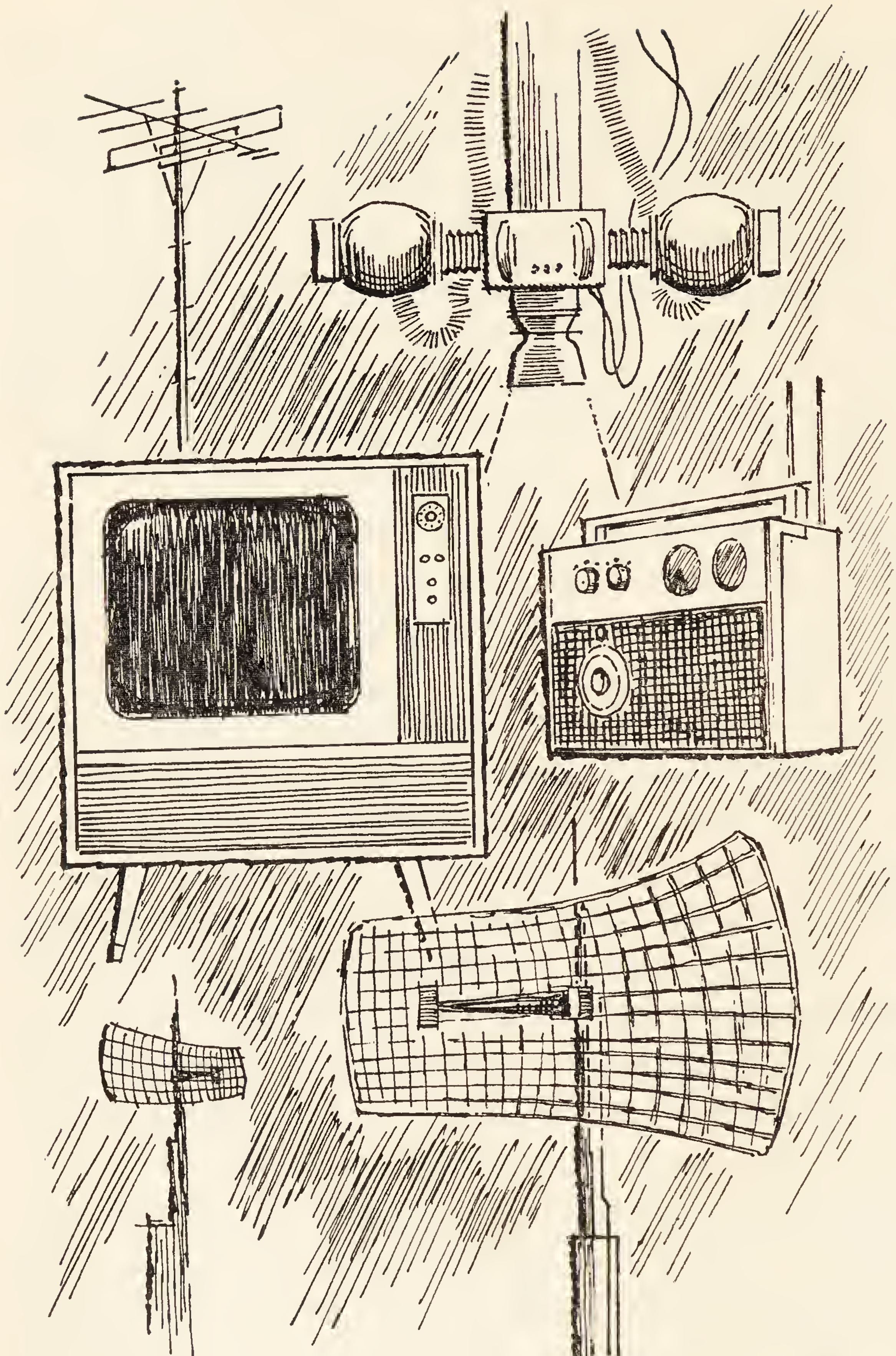
sible are known as television waves. And in both radio and television, many stations are made possible because radio and television sets can be made sensitive to broadcasts of different electromagnetic wavelengths.

Another modern device, developed to send out electromagnetic waves and to receive the echoes when they return, is radar. Since the speed of electromagnetic waves is known, the time it takes for an echo to return to the radar set can tell the operator how far away a plane is from his set.

Radar waves are extremely short, being about one-third of an inch to ten inches long; for this reason they are known as *microwaves* ("micro" means "small"). Radar is given the credit for saving Great Britain during World War II, for it warned of enemy planes in time for English planes to get into the air to intercept and destroy them. Thus, James Clerk Maxwell had made discoveries that later protected his homeland.

Storms can also be tracked with radar, and speeding motorists on America's highways are frequently detected by radar, too. When scientists started working seriously on radar after World War I, they turned to the equations in Maxwell's papers on electromagnetism, which helped guide them in their work.

Every day, hospitals are making greater use of electromagnetic waves. X rays are electromagnetic in character, being among the waves that are shorter than visible light; they make it possible to "see through" the outer surface of the human body. Wilhelm Röntgen, an outstanding German physicist, discovered X rays in 1895



Valuable instruments made possible by electromagnetic waves—television, X-ray machines, radio, and radar.

when performing electrical experiments. Today they are used not only to study bones and organs inside the human body but also to destroy cancer cells. Little did Maxwell know that certain electromagnetic waves would one day help fight the very disease that took his life.

Infrared waves, or heat waves as they are also called, provide the operating energy for some ovens, stoves, and other cooking and heating devices. Steaks can be broiled by the electromagnetic waves that are infrared rays; and enamel finishes can be baked onto household appliances by them. Infrared rays are longer than the waves that make up the spectrum we can see through a prism.

When rockets are launched into the sky, their motors create huge quantities of heat. The heat waves from these motors are infrared radiation, and they are capable of traveling far out into space. Since they can be detected by sensitive instruments, United States space scientists have been developing a space satellite that can detect a rocket launching almost as soon as the rocket engines are started. Thus, a warning station against rocket attacks may eventually come into being.

Early in the twentieth century, the brilliant German physicist Max Planck developed a new theory to explain how light travels. Planck's quantum theory does not mean that the work of Maxwell was in error, as some men have mistakenly supposed. Instead, the quantum theory and the electromagnetic theory stand side by side in explaining the character of light. In fact, it is doubtful

that anyone will ever make a discovery which can put Maxwell's work in electromagnetism on the pile of discarded theories.

It took the general public a long time to believe that there are electromagnetic waves; and it took even longer before people realized how valuable they could be. Today, however, with cooking appliances, cancer treatment, radio, television, radar, and communication with outer space making use of these waves, it is easy to realize why James Clerk Maxwell is now considered one of the great scientists of all time.

Major Events in James Clerk Maxwell's Life

1831—Born in Edinburgh, Scotland
1841—Enters Edinburgh Academy
1846—First scientific paper, on *Oval Curves,* is read before the Royal Society of Edinburgh
1847—Enters the University of Edinburgh
1849—Paper on *Rolling Curves* read to Royal Society of Edinburgh
1850—Paper on *Equilibrium of Elastic Solids* read to Royal Society of Edinburgh; starts at Cambridge University

1854—Finishes undergraduate work at Cambridge as Second Wrangler in mathematics; starts graduate work; develops ophthalmoscope

1855—Sends paper on *Experiments on Color* to Royal Society of Edinburgh; demonstrates color top to British Association for the Advancement of Science; reads first paper on *Lines of Force* to Cambridge Philosophical society

1856—Father dies; becomes Professor of Natural Philosophy at Marischal College, Aberdeen, Scotland

1857—Wins prize for theory on Saturn's rings

1858—Marries Katherine Mary Dewar

1860—Loses post at Marischal College; becomes Professor of Natural Philosophy at King's College, London; demonstrates color box to British Association for the Advancement of Science; has smallpox; receives Rumford Medal from the Royal Society of London for achievements in field of color vision

1863—Supervises work that establishes a standard for the ohm

1865—Injured in riding accident; retires from teaching to devote his time to research and writing at Glenlair

1866—Supports molecular theory of physics and introduces statistical method in studying molecules in paper on *Viscosity of Gases*

1867—Starts tour of cities and leading science laboratories of Europe

1868—Returns to Glenlair from tour of Europe

1871—Returns to academic life to supervise building of Cavendish Laboratory at Cambridge and to set up new department of physics; publishes *A Treatise on Heat*, a textbook

1873—Publishes his most important book, *A Treatise on Electricity and Magnetism*, in which he expresses his theories of electromagnetism and light in their final form

1876—Publishes *Matter and Motion*, a textbook expressing his final views on molecular physics

1879—Publishes the papers of Henry Cavendish; dies at Cambridge

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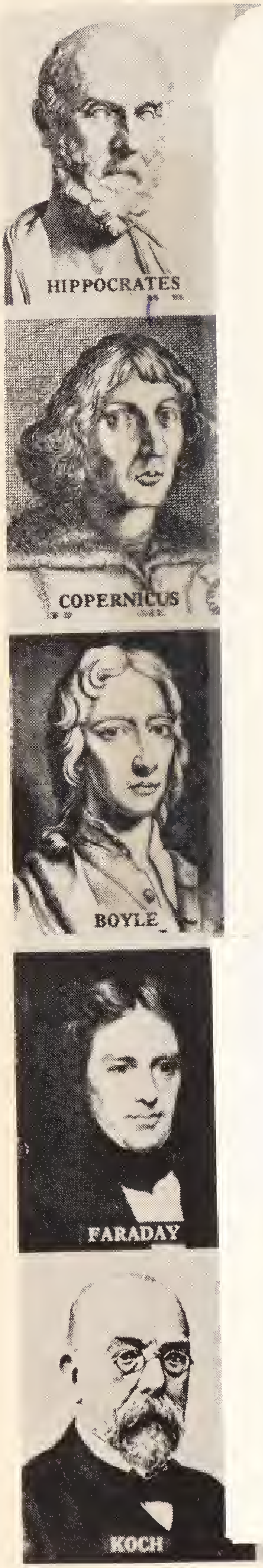

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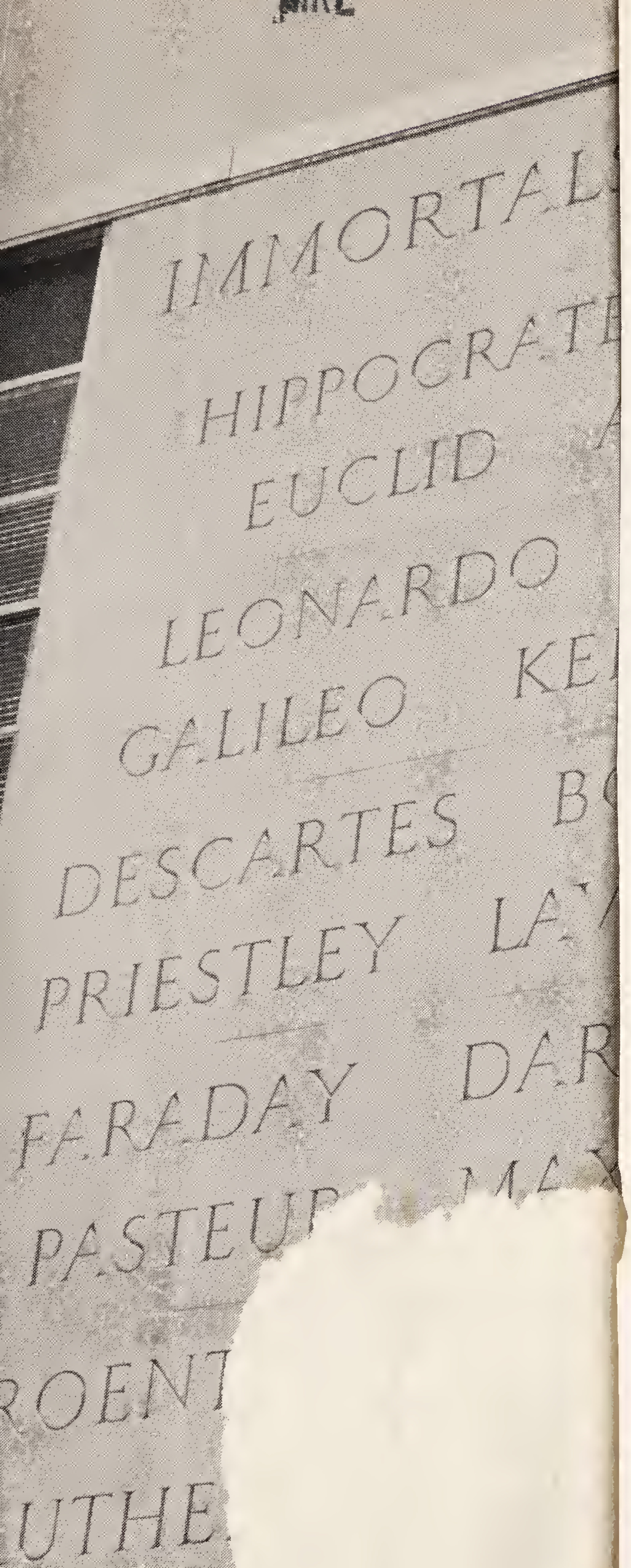
TALS OF SCIENCE



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CHARLES PAUL MAY was born in Bedford, Iowa, and attended Drake University in Des Moines. Upon graduation, he attended Oklahoma A. & M.; later, he taught there and at Ohio University. Currently he is with the editorial staff of *The Book of Knowledge*, and regularly reviews books in many newspapers.

Each new IMMORTALS OF SCIENCE biography stresses the *contributions* of a great figure in history. Each shows how those contributions improved the world of yesterday, and the importance of their impact on life today. Each is carefully written and edited to provide a clear and lasting portrait of its subject.

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THE IMMORTALS OF SCIENCE

The Science Wall of Honor at the University of Bridgeport has provided the inspiration for titling this new series of science biographies. The monument honors 25 of the most important 'Immortals of Science' by displaying their names on a new science building. These 25 men were chosen in a world-wide poll of more than 1100 qualified scientific electors.

Aimed primarily at the reader who has reached the stage in life where he is 'impatient to be grown up' and do important things himself, the IMMORTALS OF SCIENCE Biographies are both informative and inspirational. The reader is given a clear concept of the period when the particular scientist lived; his early life, education, and his quest for new facts is told in such a manner that the reader himself *experiences* the entire process. Sufficient is told of the subject's scientific accomplishments to provide the inquiring mind with a good knowledge of the history of science — and this alone makes the series unique. Too many biographies of scientists for young people seem more concerned with inconsequential details than in telling the all-important scientific story. Indeed, the history of science is an indispensable segment of the history of all mankind's civilization.

These biographies are recommended for school libraries and for the children's departments of public libraries. They are admirably suited for home library collections. All are well-indexed; some contain chronological summaries and glossaries of technical terms.

— *Hilary J. Deason, Director*
Science Library Program
American Association for the
Advancement of Science